5th CERN-Fermilab Hadron Collider Physics Summer School

Fermilab - August 27, 2010

Direct Dark Matter Detection

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outline

- why dark matter?
  - motivation
  - popular candidates for dark matter, WIMPs
- direct WIMP dark matter detection
  - a flavor of the experimentalist's approach to the problem
  - current experimental status (with controversies)
  - review of current experiments (personal cut)
  - key features: strategies and technology
- outlook

introductory remarks

- inevitably, this is only an overview of the subject

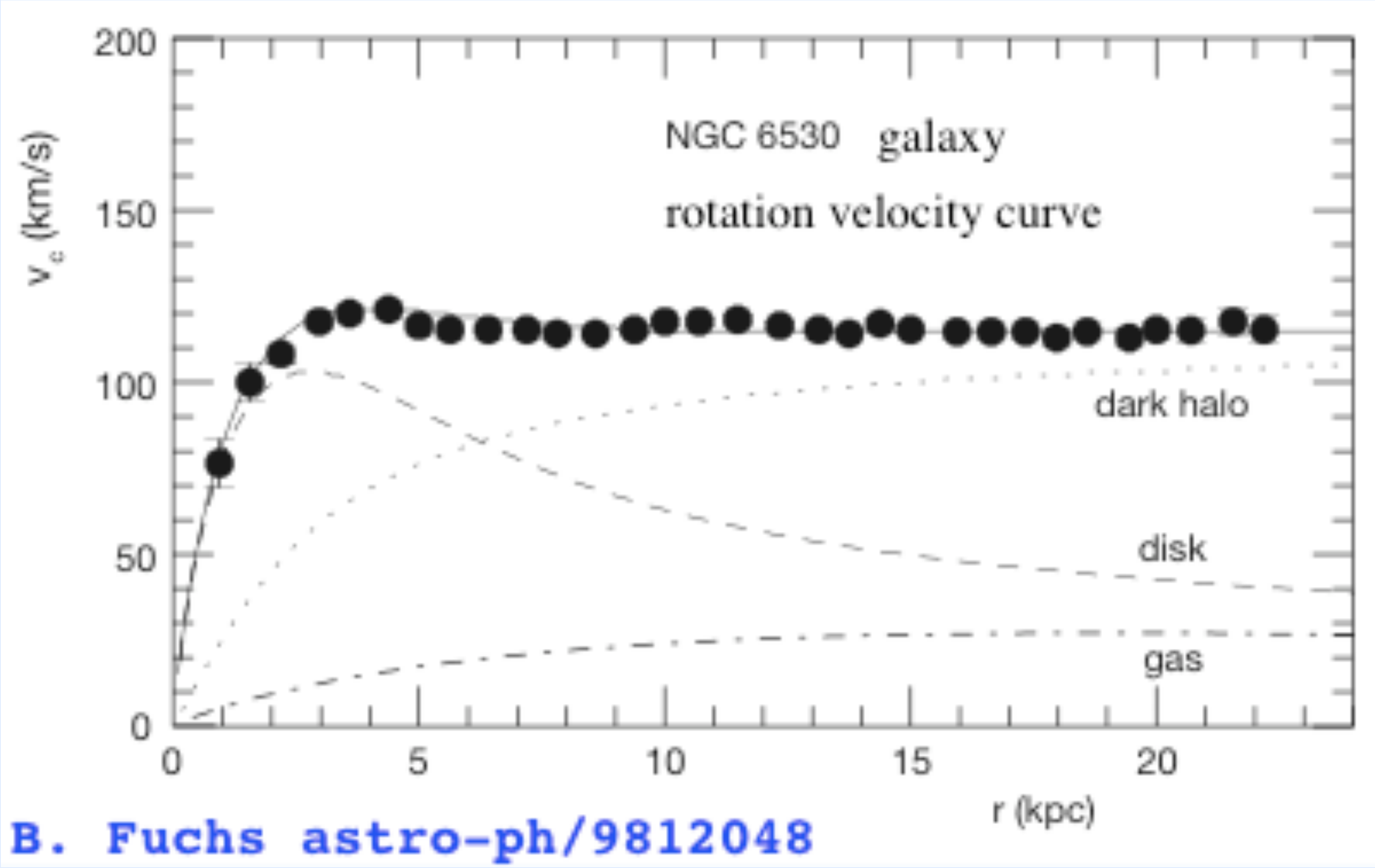
- many details of dark matter models are still being debated and are not discussed here

- I am honored to close this collider school talking about non-accelerator physics

- wait until the end for some piece of trivia and wisdom!

mass budget of the universe

there is excellent evidence that most matter in the universe is dark, i.e. does not interact electromagnetically

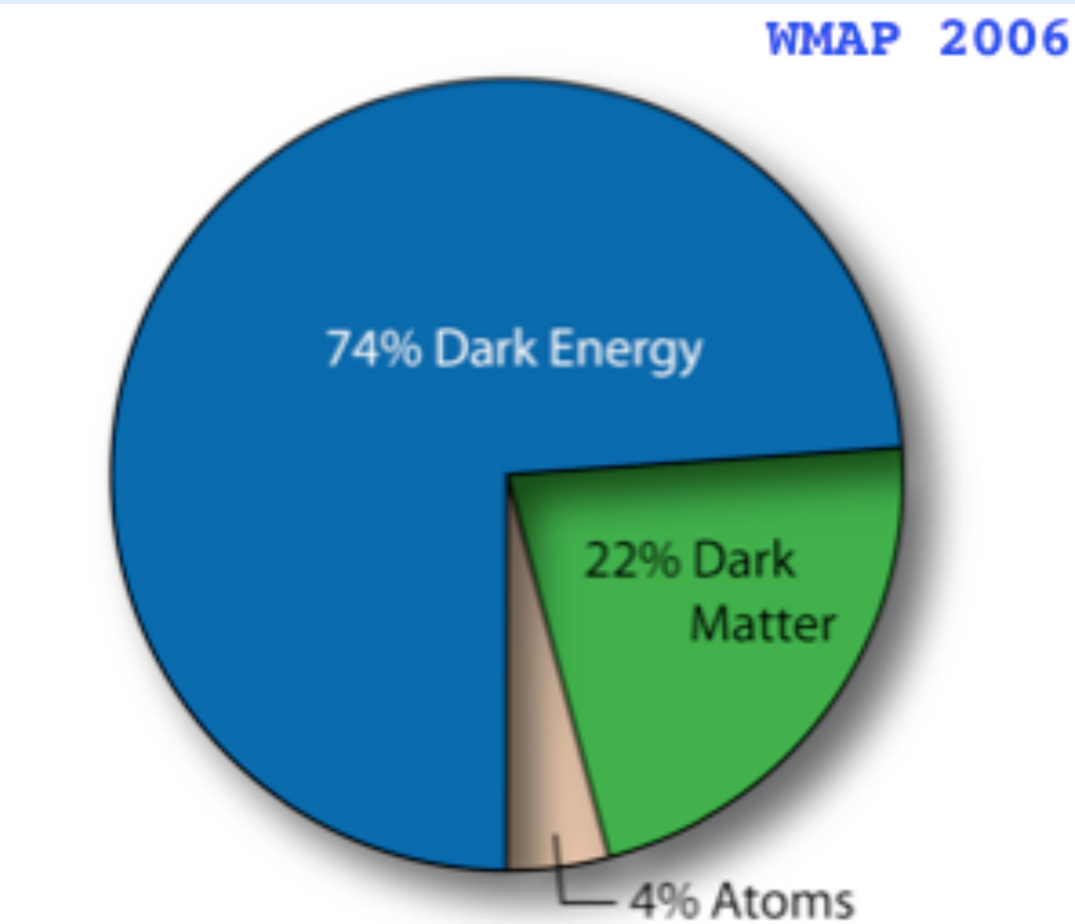


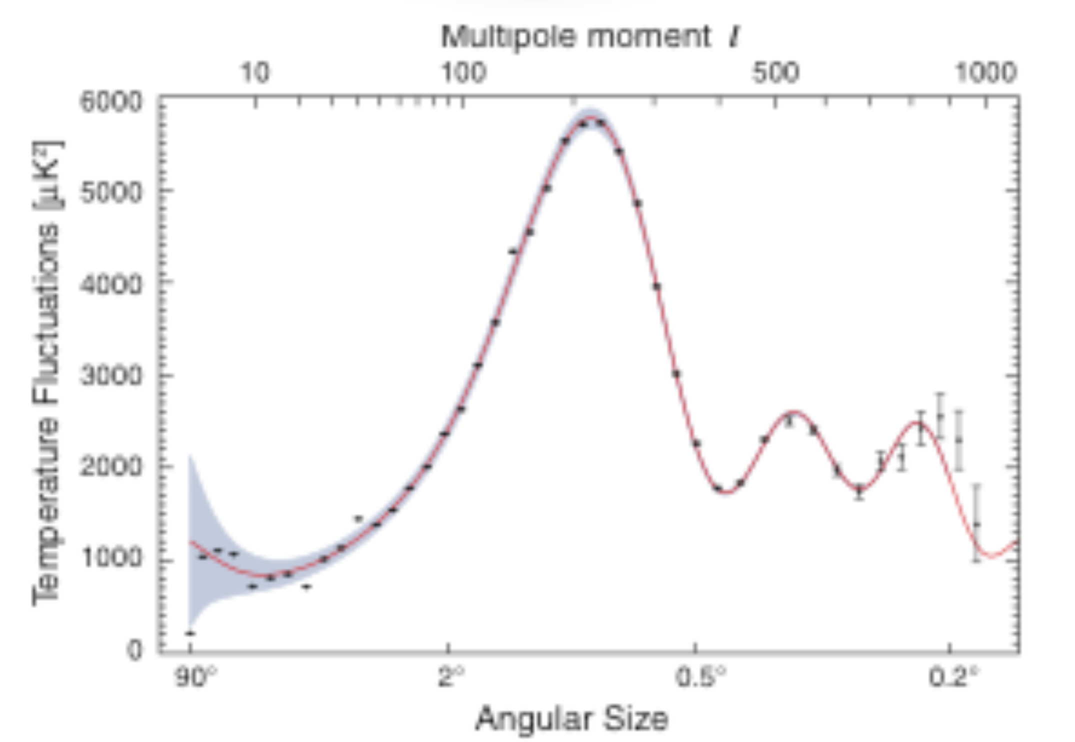
(behavior observed for many galaxies)

- galaxy rotation velocity curves do not show the fall-off expected if all the gravitational pull were from the visible matter alone

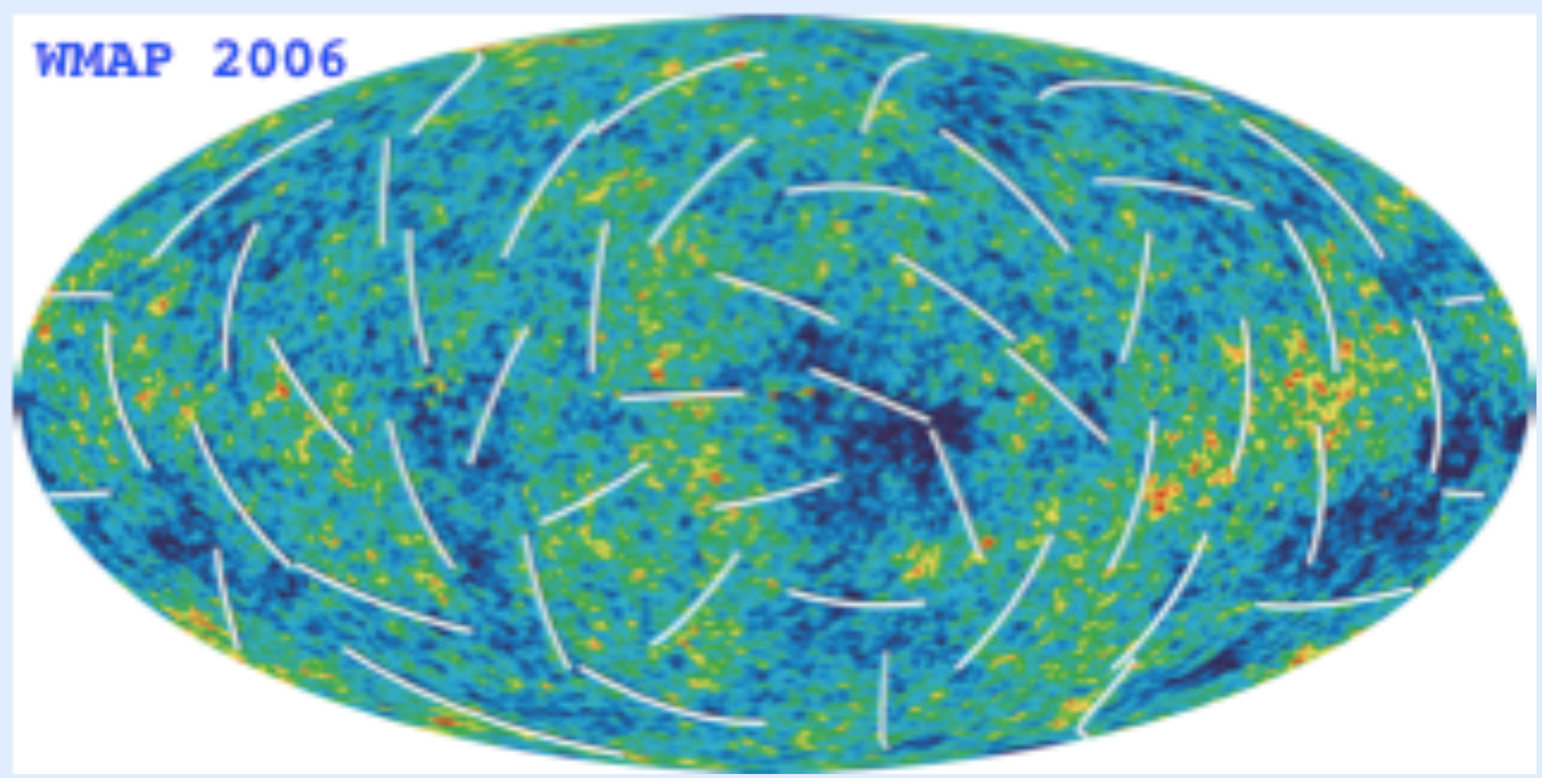
- the constant velocity out to very large radius suggests the existence of a dark, massive halo

evidence at the cosmological scale

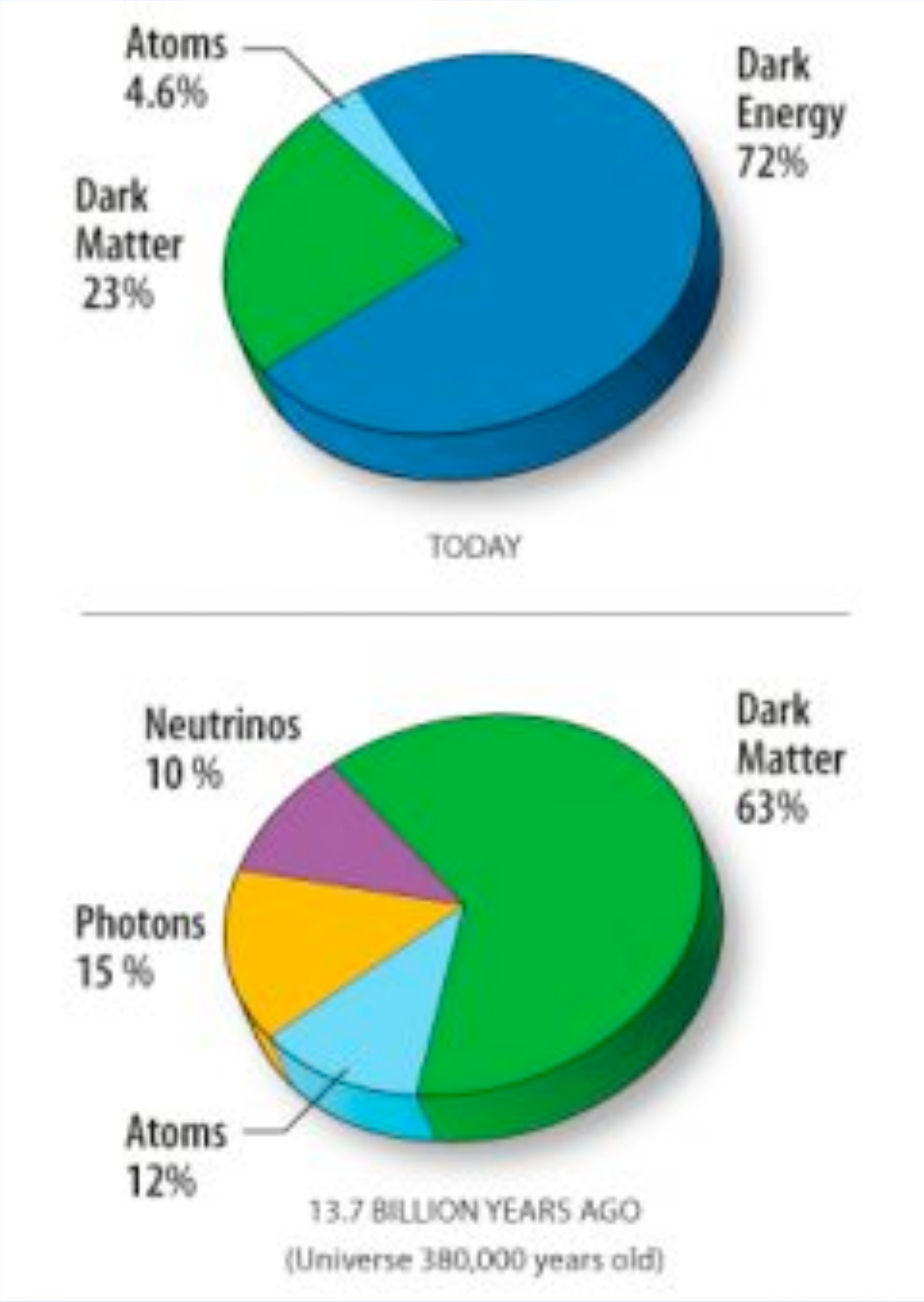




- the WMAP measurements of the cosmic microwave background fluctuations provides beautiful data from which to infer that most of the energy density in the universe is unknown
- ~85% of massive matter is dark
- massive neutrinos are not enough to account for the missing part

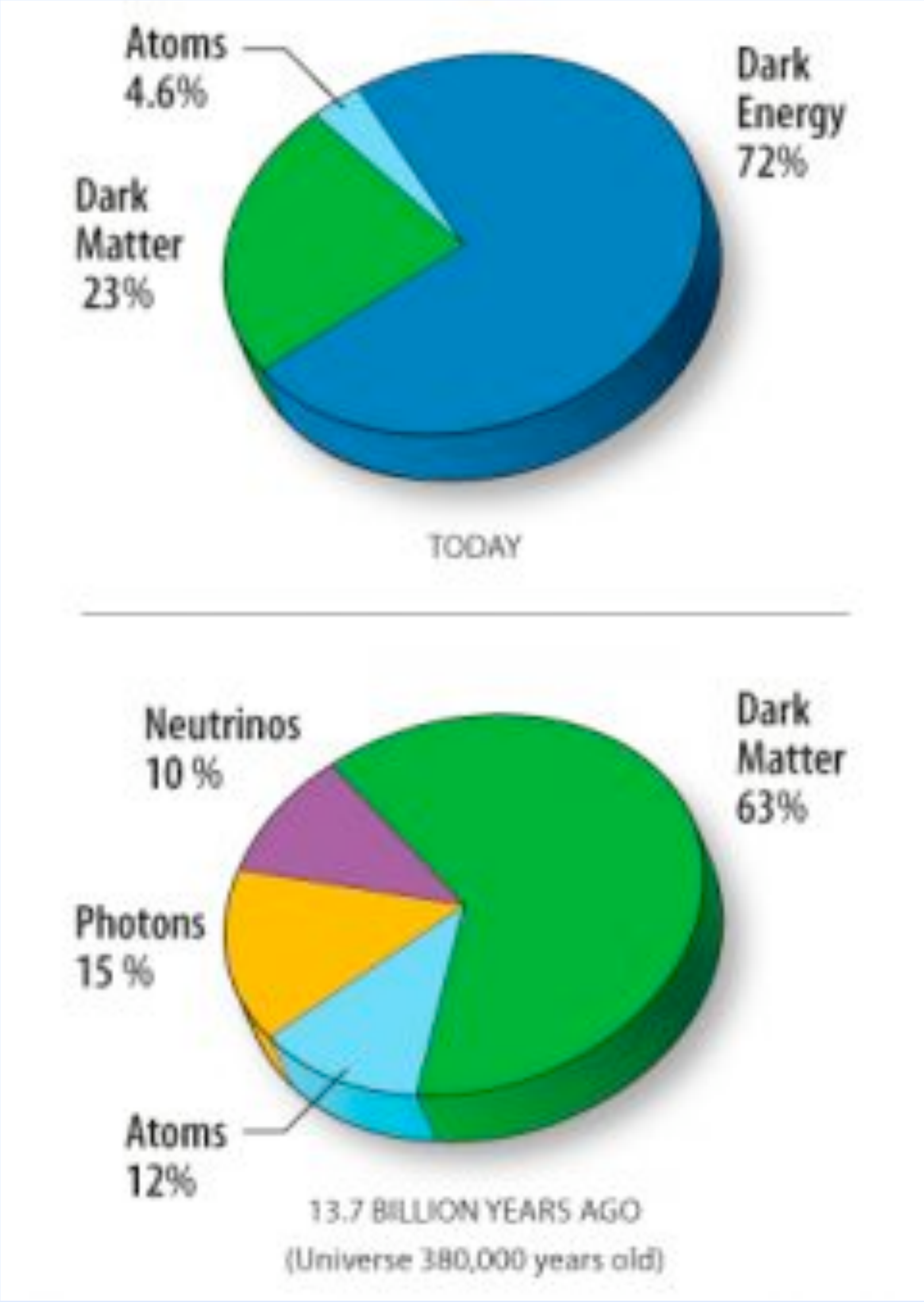


are neutrinos dark matter?



- neutrinos are too light (relativistic) to explain observed large scale structure
- atoms (baryonic matter), photons and neutrinos add up to ~1/3 of the what is needed (at WMAP time)

are neutrinos dark matter?

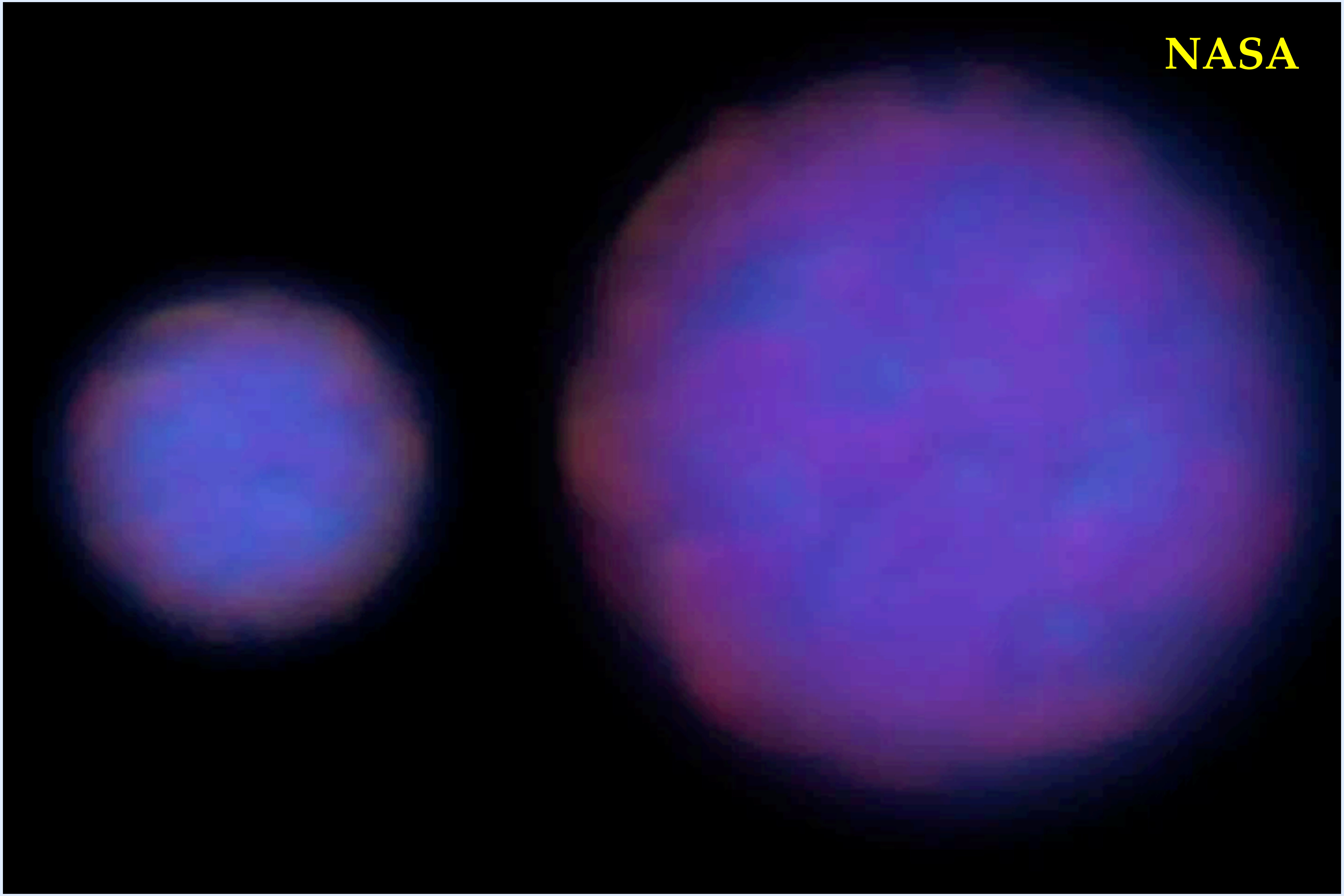


- neutrinos are too light (relativistic) to explain observed large scale structure
- atoms (baryonic matter), photons and neutrinos add up to ~1/3 of the what is needed (at WMAP time)
- compelling candidates for dark matter are weakly interacting massive particles (WIMPs)
  [after all, MACHOs were not found, so you look in the opposite direction!]

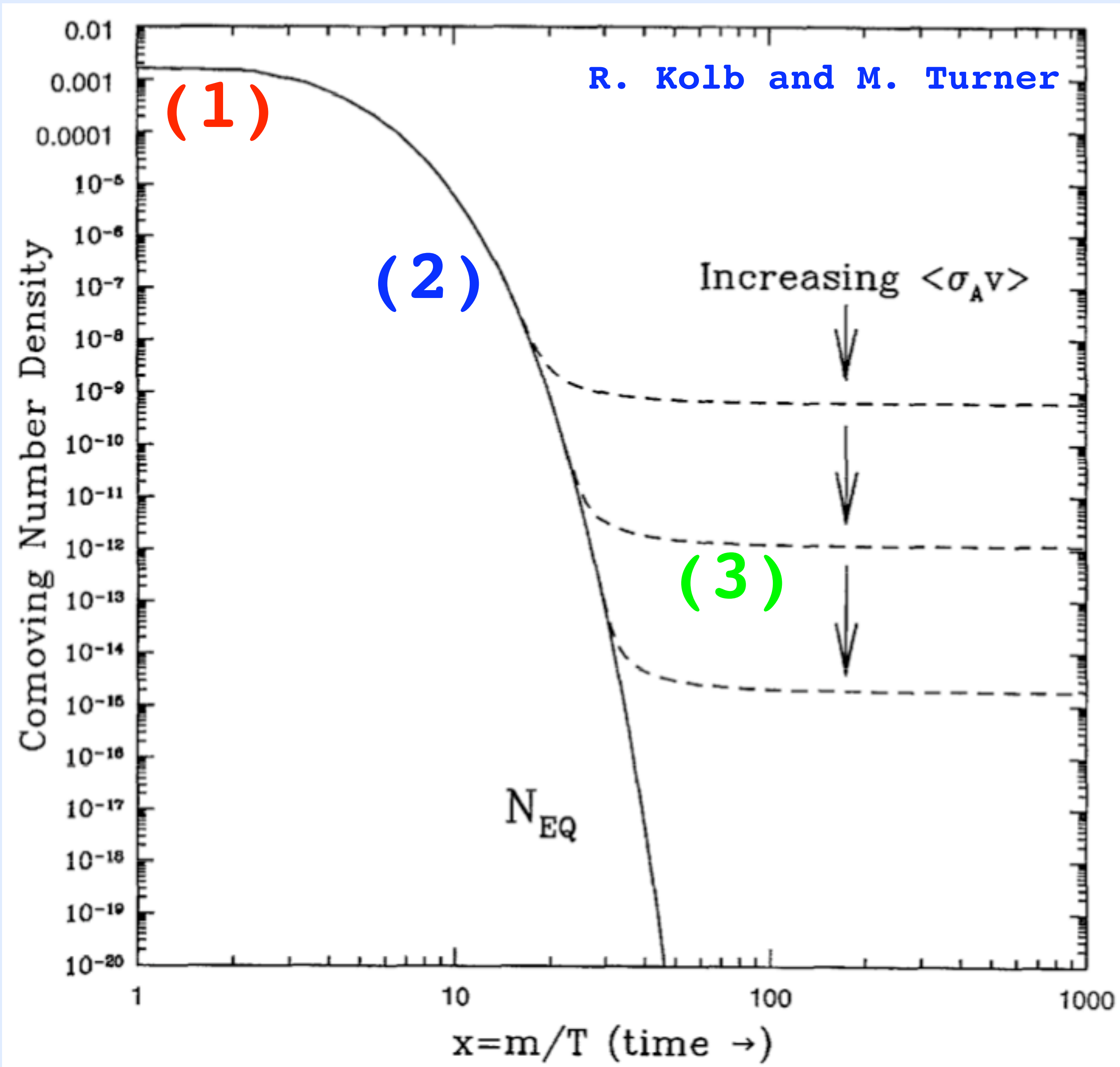
evidence for dark matter (Bullet Cluster)

evidence for dark matter (Bullet Cluster)

colliding clusters of galaxies (simulation)



particle candidate: WIMPs (Weakly Interacting Massive Particles)



- relic stable particle produced in thermal equilibrium in the early universe

- WMAP: $0.095 < \Omega_\chi h^2 < 0.129$
- $\Omega_\chi h^2 \sim (\langle\sigma_\chi v\rangle_{\text{freezout}})^{-1}$
- $\langle\sigma_\chi v\rangle_{\text{freezout}} \sim 3\times10^{-26}\ \text{cm}^3/\text{s}$

- weak scale cross section gives the right relic abundance (inversely proportional to the annihilation cross section)
- $\langle\sigma_\chi v\rangle \sim 10^{-25}\ \text{cm}^3/\text{s}$

($\sigma_\chi \sim 10^{-37}\ \text{cm}^2$ weak scale)

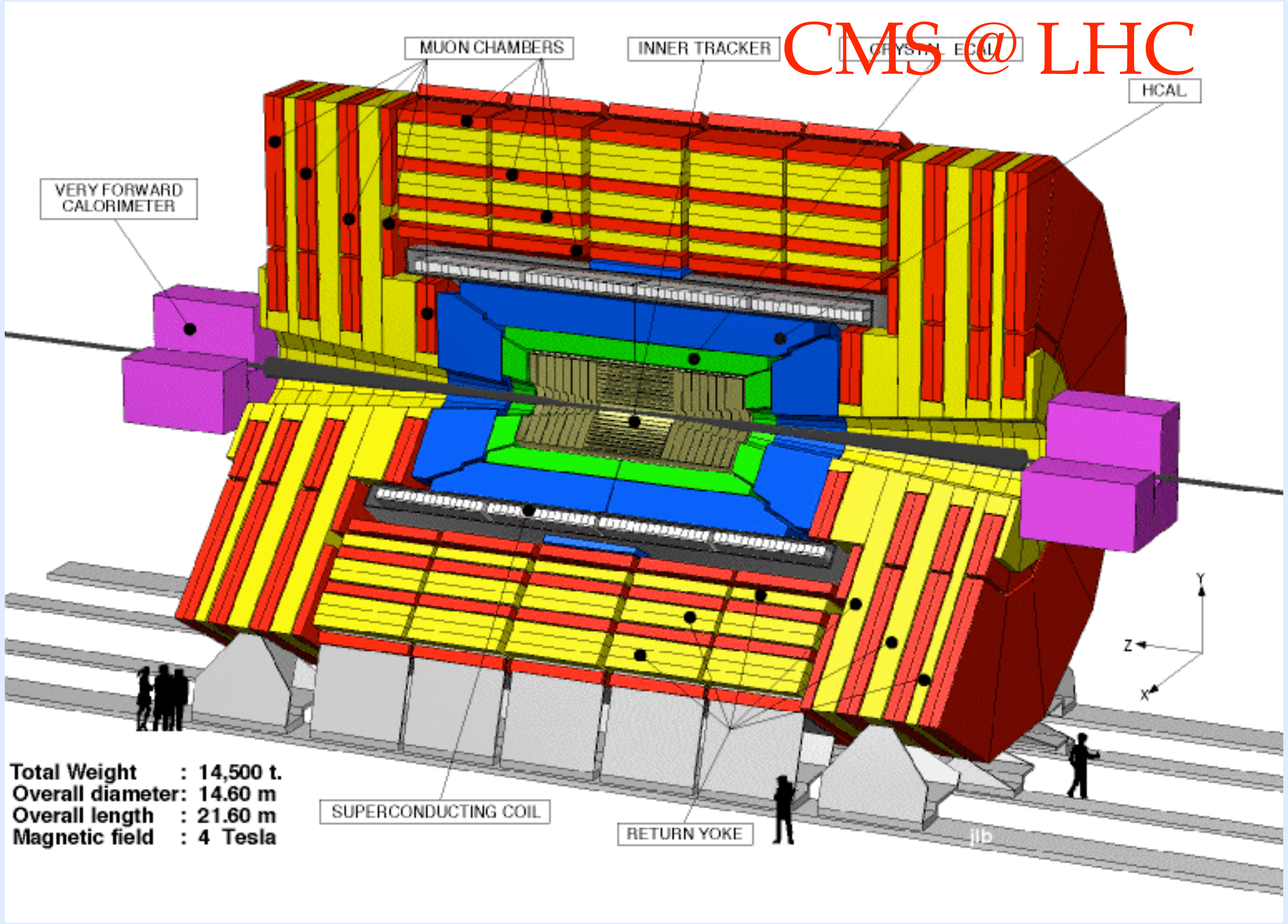
(1) Equilibrium
$\chi\chi \Leftrightarrow \bar{f}f$

(2) Eq. Cooling
$\chi\chi \Leftrightarrow \bar{f}f$

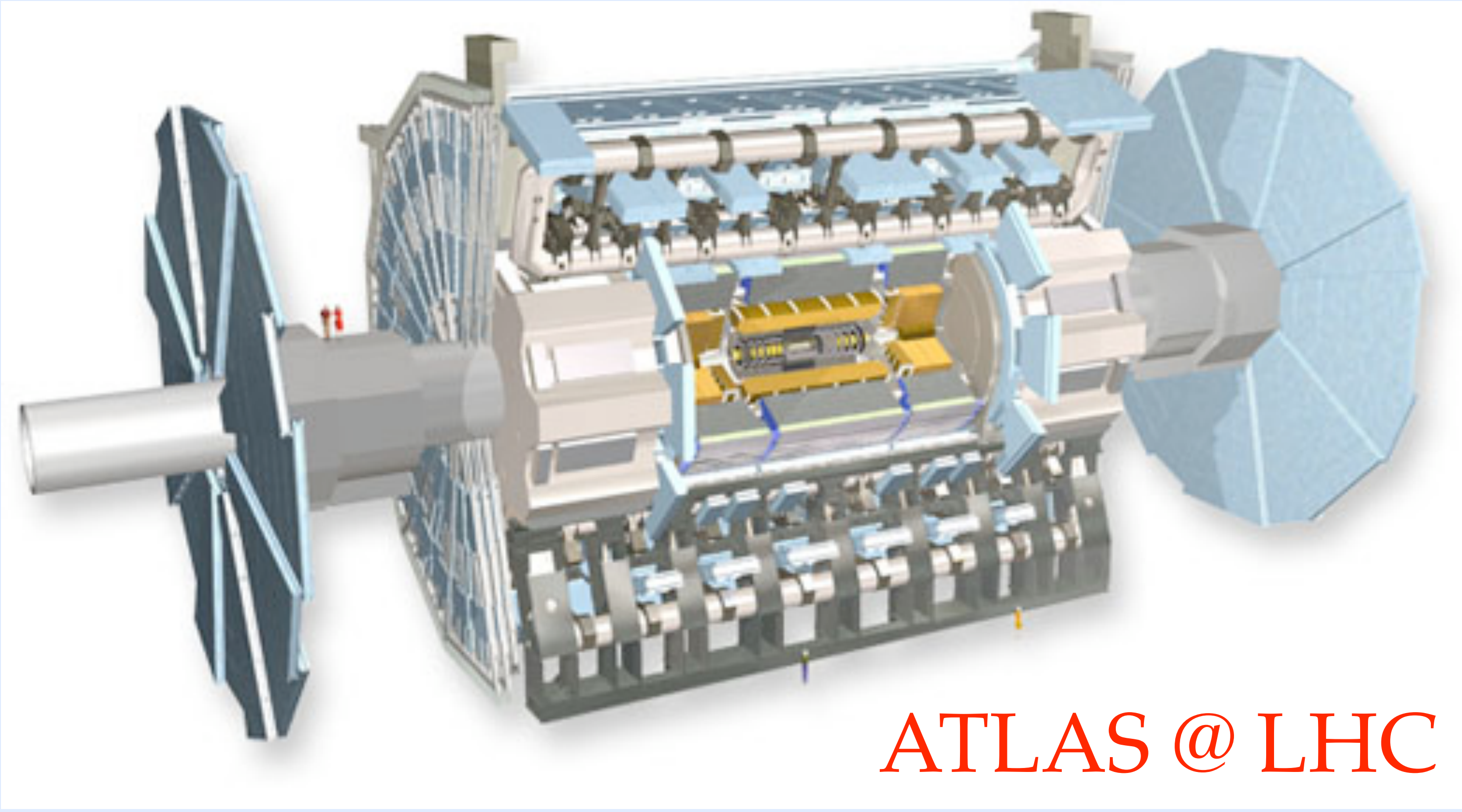
(3) Freeze-out
$\chi\chi \not\Leftrightarrow \bar{f}f$

detecting dark matter

Cosmological observations give us substantial evidence for dark matter. It is important to understand what this matter is.

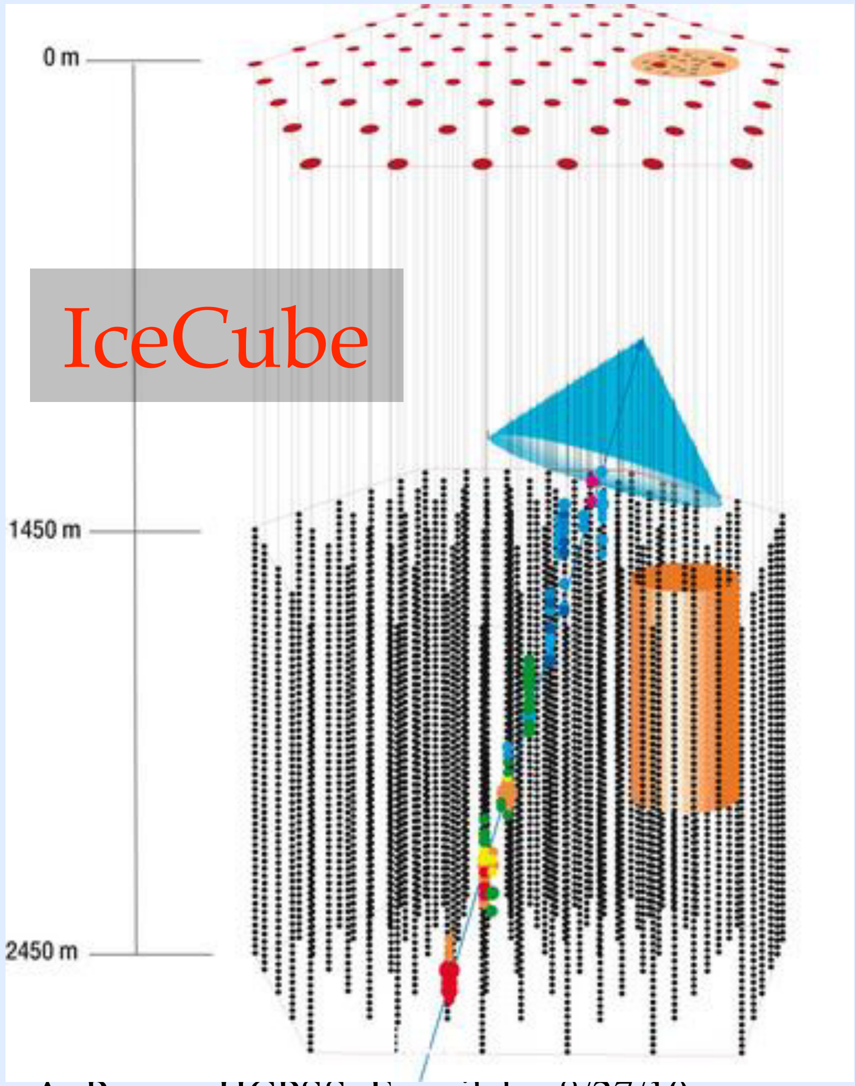


1. produce it at accelerators (LHC), maybe in the form of supersymmetric (SUSY) particles This effort has been ongoing for many years (LEP, Tevatron) at ever increasing energies



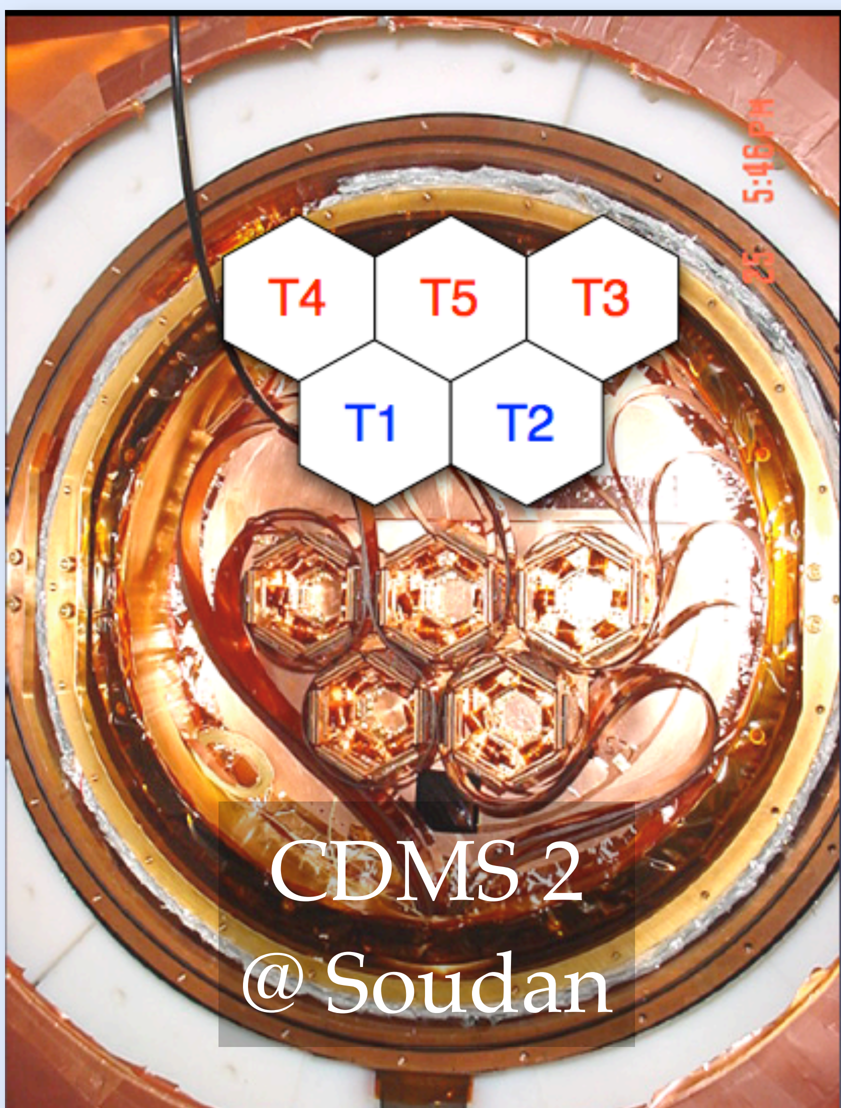
detecting dark matter

2. observe its annihilation products ($e^{\pm}$, γ rays, neutrinos, ...) in the Sun and our galaxy
This is done by experiments such as HEAT, PAMELA, GLAST/Fermi, EGRET, VERITAS, HESS, MAGic, AGIS, IceCube



detecting dark matter

3. directly detect dark matter particles interacting with detectors in the laboratory

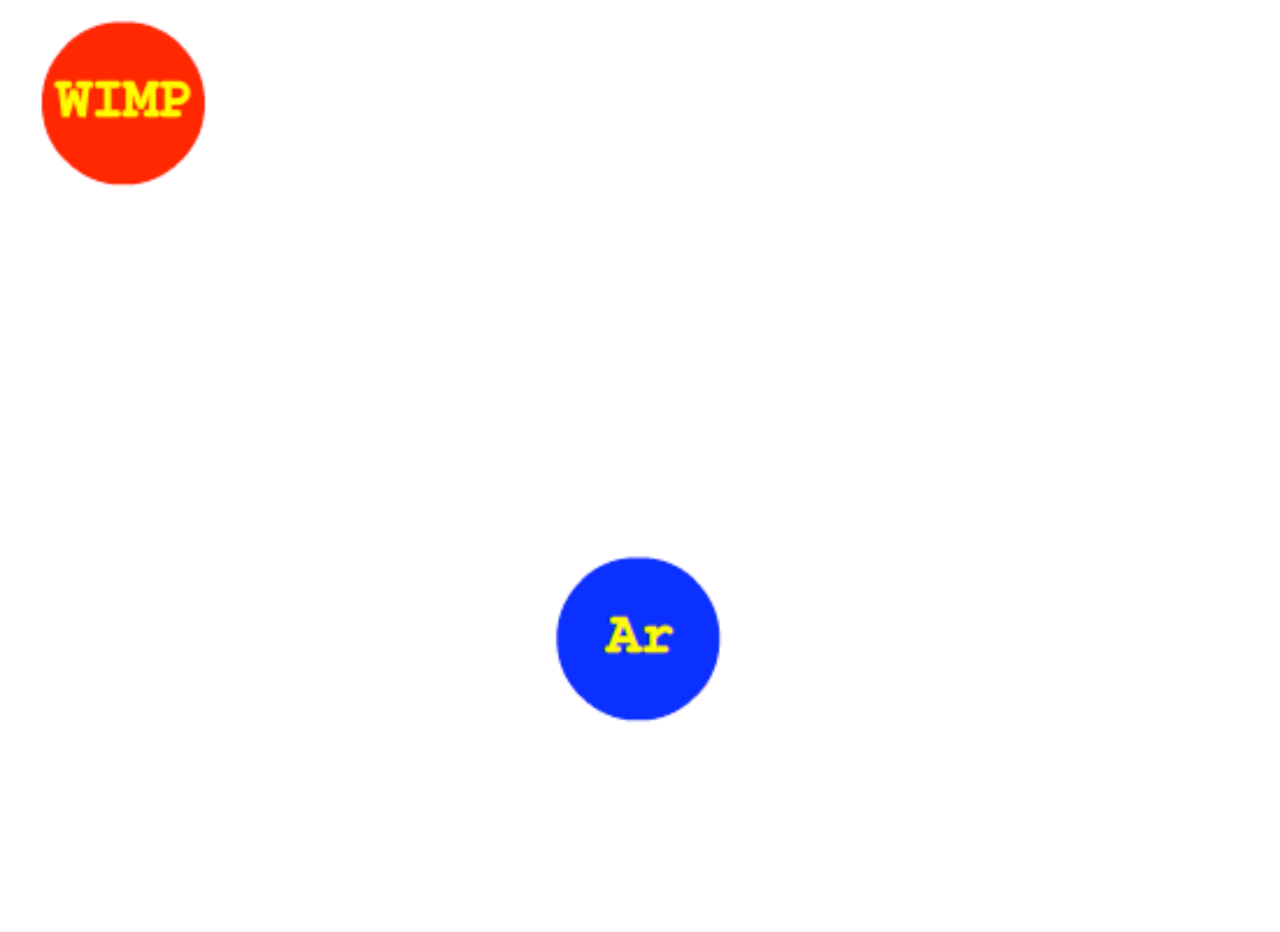


WIMP coherent scattering on nuclei

3-bis. direct detection of the elastic scattering recoil of nuclei in a crystal, liquid or gas.

A 100 GeV WIMP particle in the halo of our galaxy (300 m/s) imparts few-to-tens of keV kinetic energy to a ~100 amu nuclear target (Ar, Ge, I, Xe)

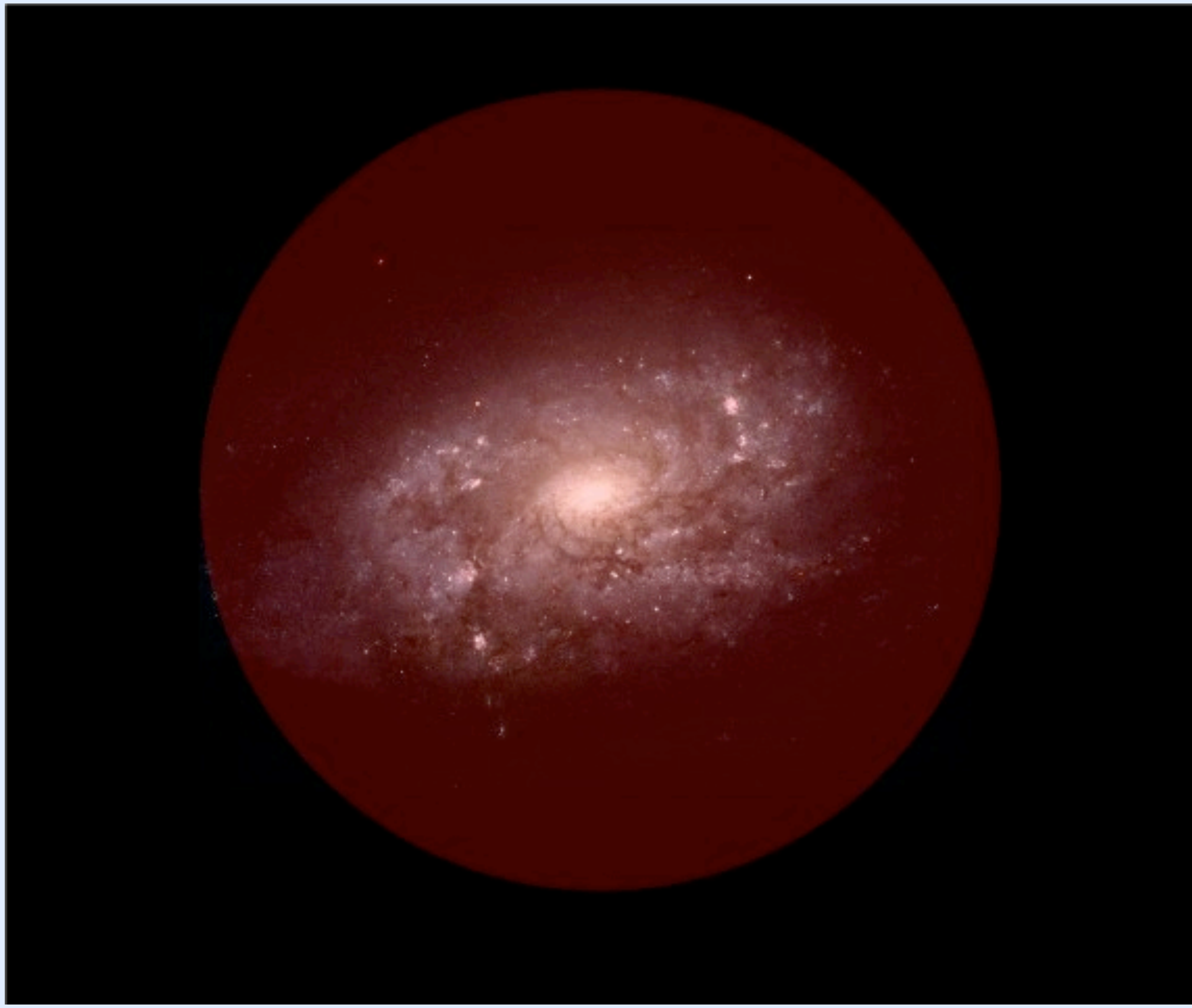
just billiard balls:



(this interaction actually has its subtleties)

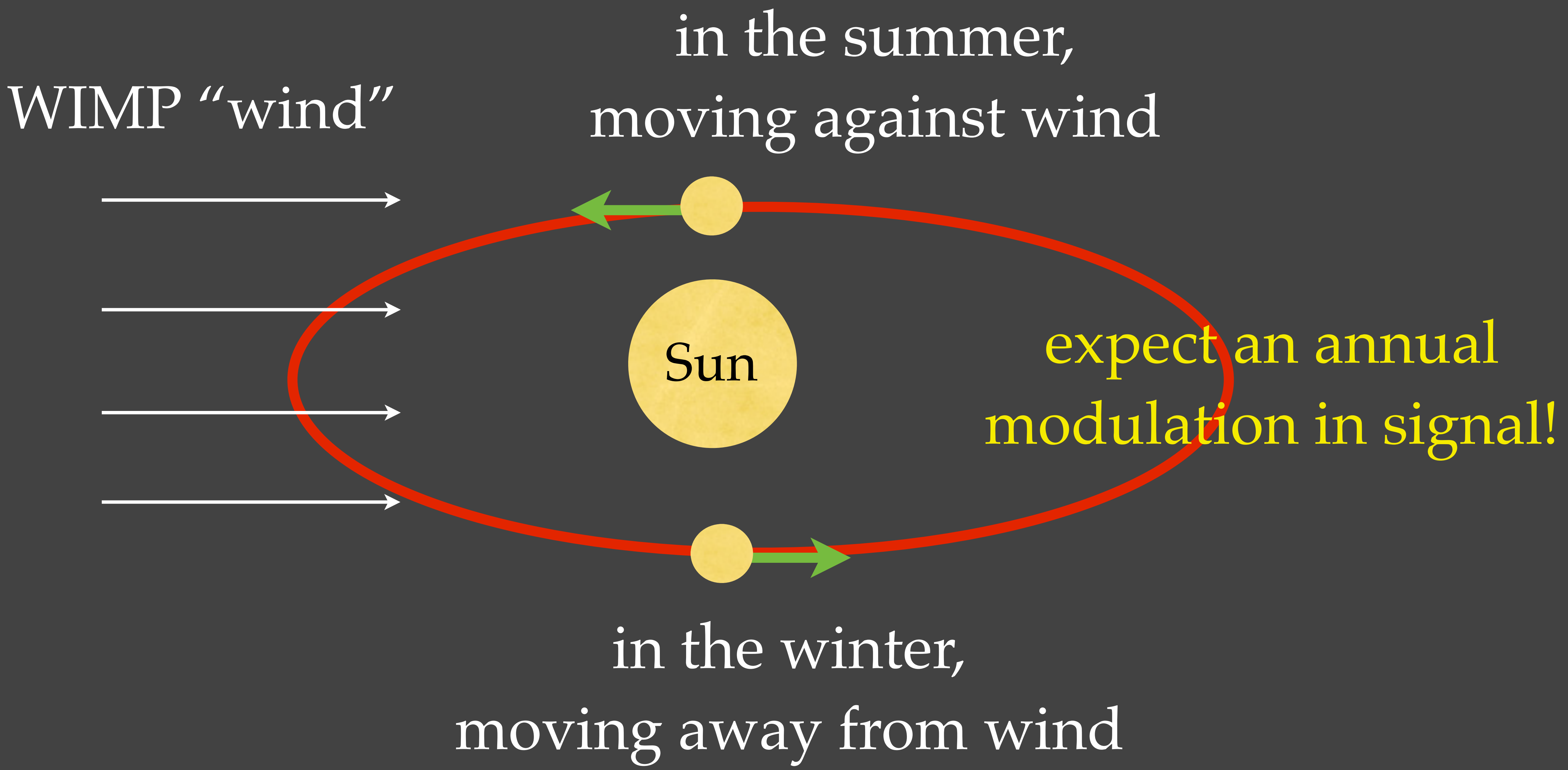
dark matter galactic distribution

- spherical halo
- local density of WIMPs
~0.3 GeV/cm^3 (~3×10^5 protons/m^3)
- assume Maxwell-Boltzmann
velocity distribution
- v_{escape} ~ 650 km/s
(WIMP escape velocity from halo)
- v_{escape} ~ 220 km/s
(WIMP velocity on detector, non
relativistic)
- rate and energy spectrum depend
on WIMP distribution and velocity



- there are many versions of this
model, but it is important to pick one
in order to compare experimental
results

WIMP wind and signatures



Drukier, Freese, and Spergel Phys.Rev. D **33**, 3495 (1986) *now I will turn my focus mainly on the detection of spin-independent WIMPs in large, quiet detectors*

coherent scattering (from simple quantum mechanics)

nuclear radius: $R \sim r_0 A^{1/3} \sim 7$ fm ($r_0 \sim 1.5$ fm, A=100)

WIMP de Broglie wavelength (non-relaticvistic):
$\lambda = h/p \sim h/mv \sim 6.6\times10^{-34}$ J s / 3.5×10^{-22} N s ~ 19 fm

WIMP interacts coherently with the nucleus: $\sigma \sim \sigma_0 A^2$

some formalism (spin-independent interaction)

Reduced Mass WIMP-Nuclide ------ $\mu_A = \dfrac{M_A M_\chi}{M_A + M_\chi}$

Reduced Mass WIMP-Nucleon ----- $\mu_n = \dfrac{m_n M_\chi}{m_n + M_\chi}$

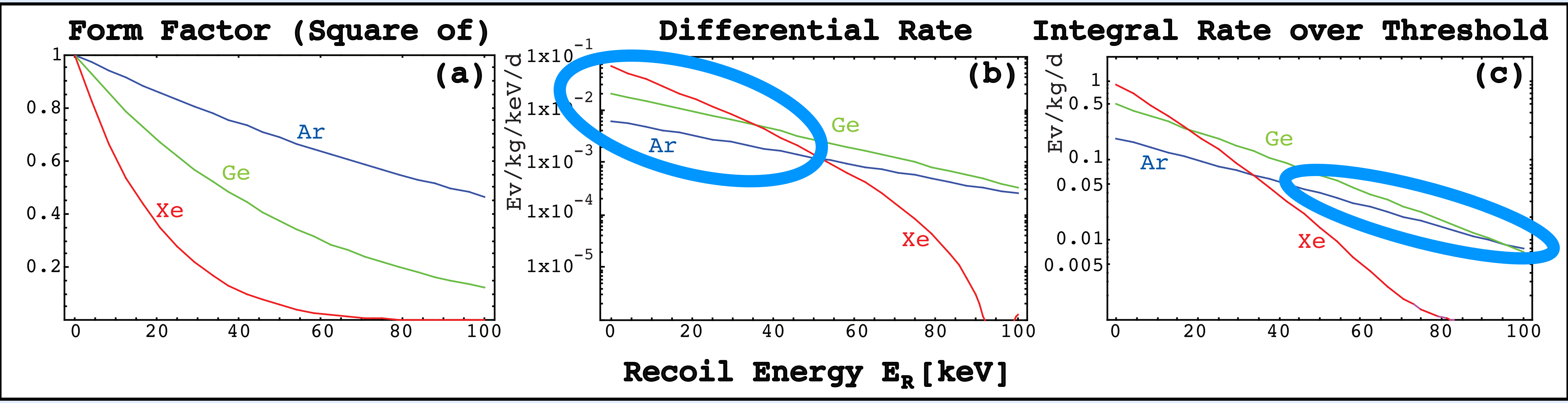
Momentum transferred -------------- $q = \sqrt{(2M_A E)}$

For zero momentum transfer -------- $\sigma_0 = \sigma_{\chi,n} A^2 \dfrac{\mu_A^2}{\mu_n^2}$

Non-null momentum transfer ------- $\sigma(q) = \sigma_0 F^2(q)$

what to look for

1. Rate per unit mass depends on atomic number A
2. Nuclear recoils spectrum depends on atomic number A
3. Yearly modulation of spectrum
4. Daily modulation of nuclear recoil directionality



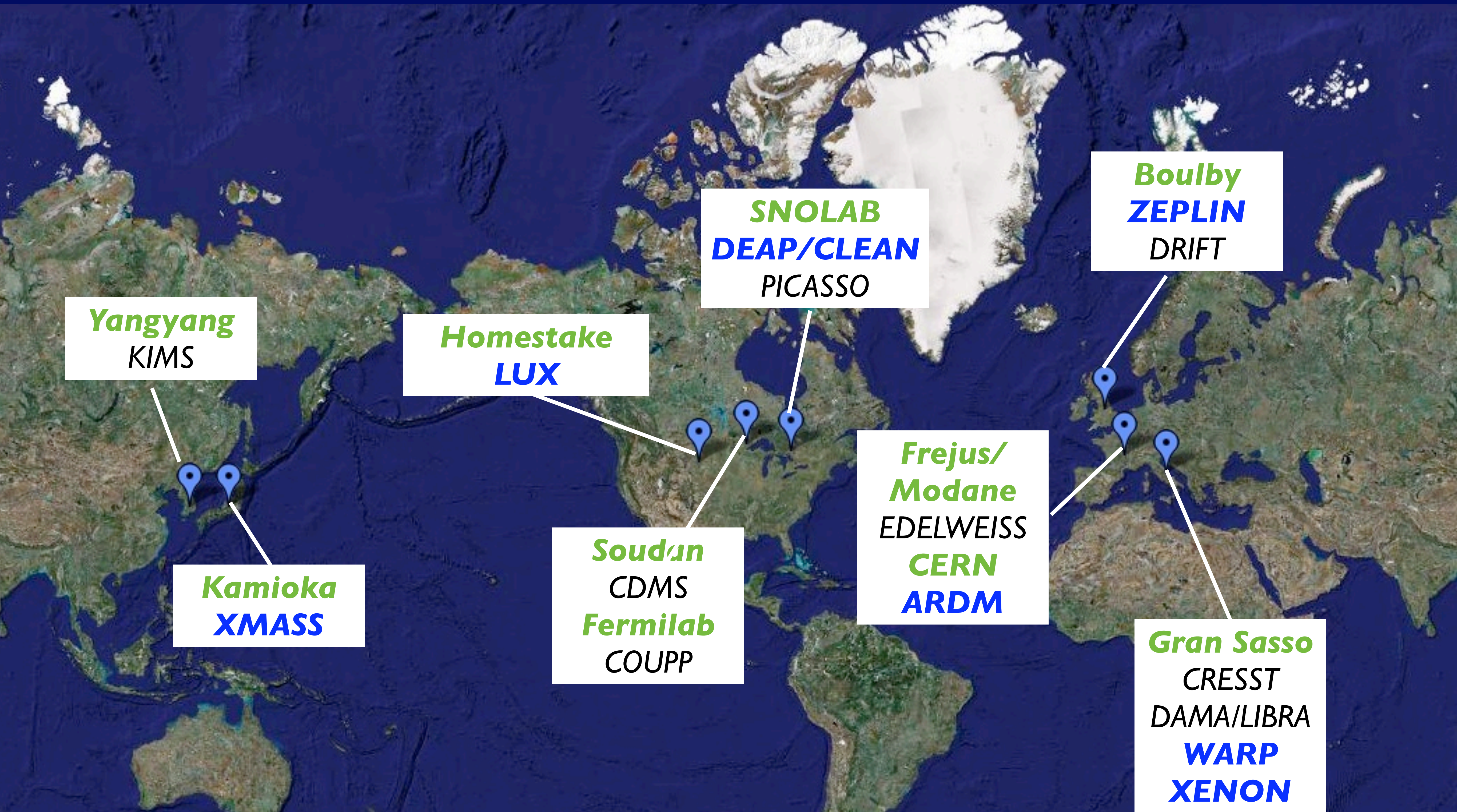
the experimentalist's approach

- follow theoretical thinking and observational results carefully, but stay open to things we have not thought about, in view of the fact that we really do not know what dark matter is

- in order to build an experiment, one needs to make specific design choices; the following is a list of things one has to consider carefully:

    - choice of target (A-dependance), multiple targets?
    - aim for large target mass
    - seasonal variation of detection rate
    - energy resolution, spectral shape, low energy threshold
    - directionality of recoil
    - maximize background rejection

direct dark matter searches



also:
CoGeNT (Soudan), TEXONO (Taiwan), DarkSide, DMTPC (WIPP)
and many other efforts, some in the R&D stage

backgrounds

strategies to overcome them

1. cosmic rays: interact in the upper atmosphere producing muons which in turn produce showers of particles along their path

underground
muon-veto detectors

2. natural radioactivity (external an internal): ubiquitous; long-lived isotopes ($^{238,235}U$, ^{232}Th, ^{40}K); cosmic activation isotopes (long- and short-lived)

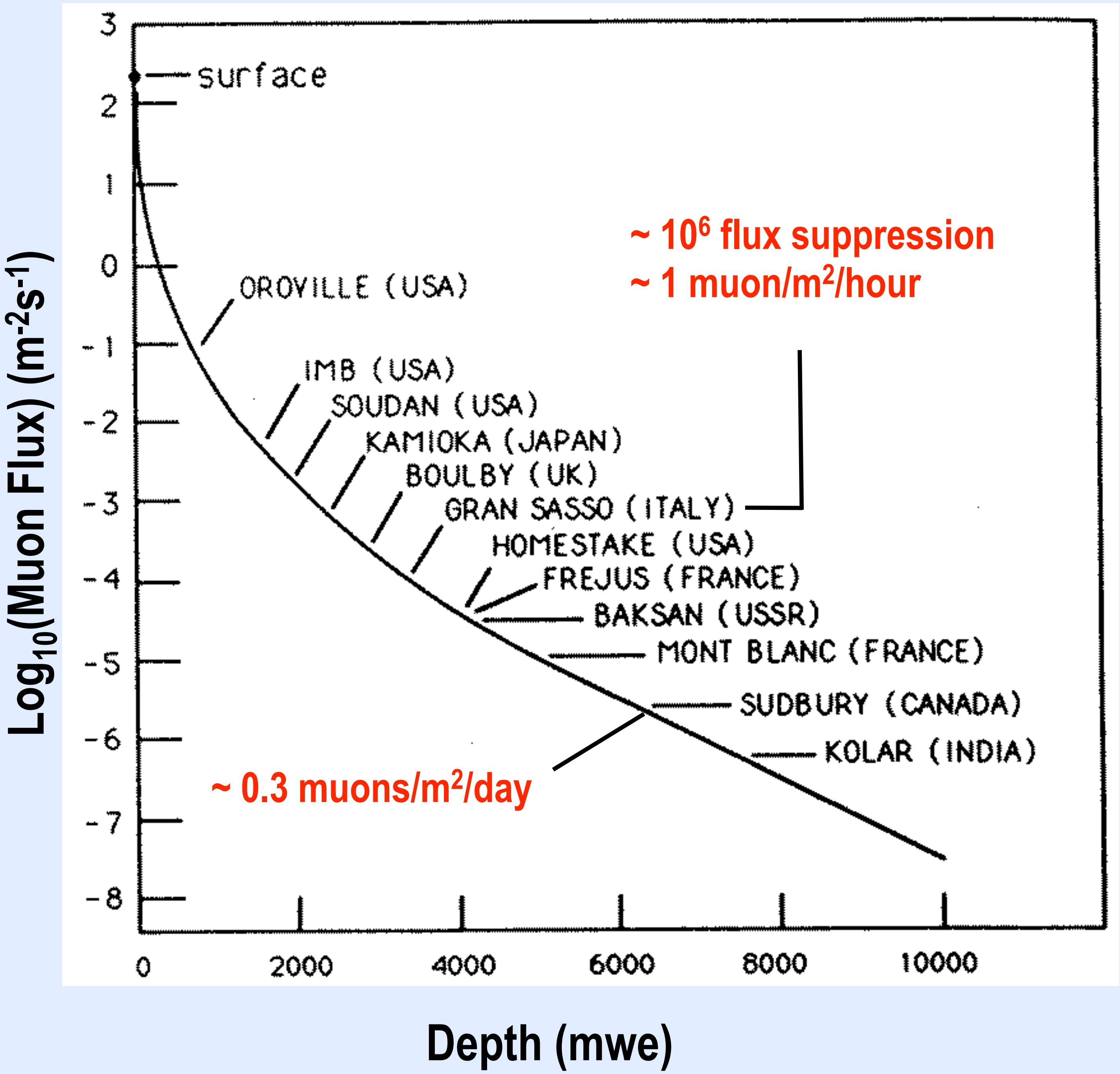
material selection
precision cleaning
underground storage
shielding

3. neutrons: produced in muon spallation or via (α,n) reactions

active and passive shielding
multiple-site event detection

coincidence with muons
particle identification

need to go deep underground



a handle on backgrounds (personal take)

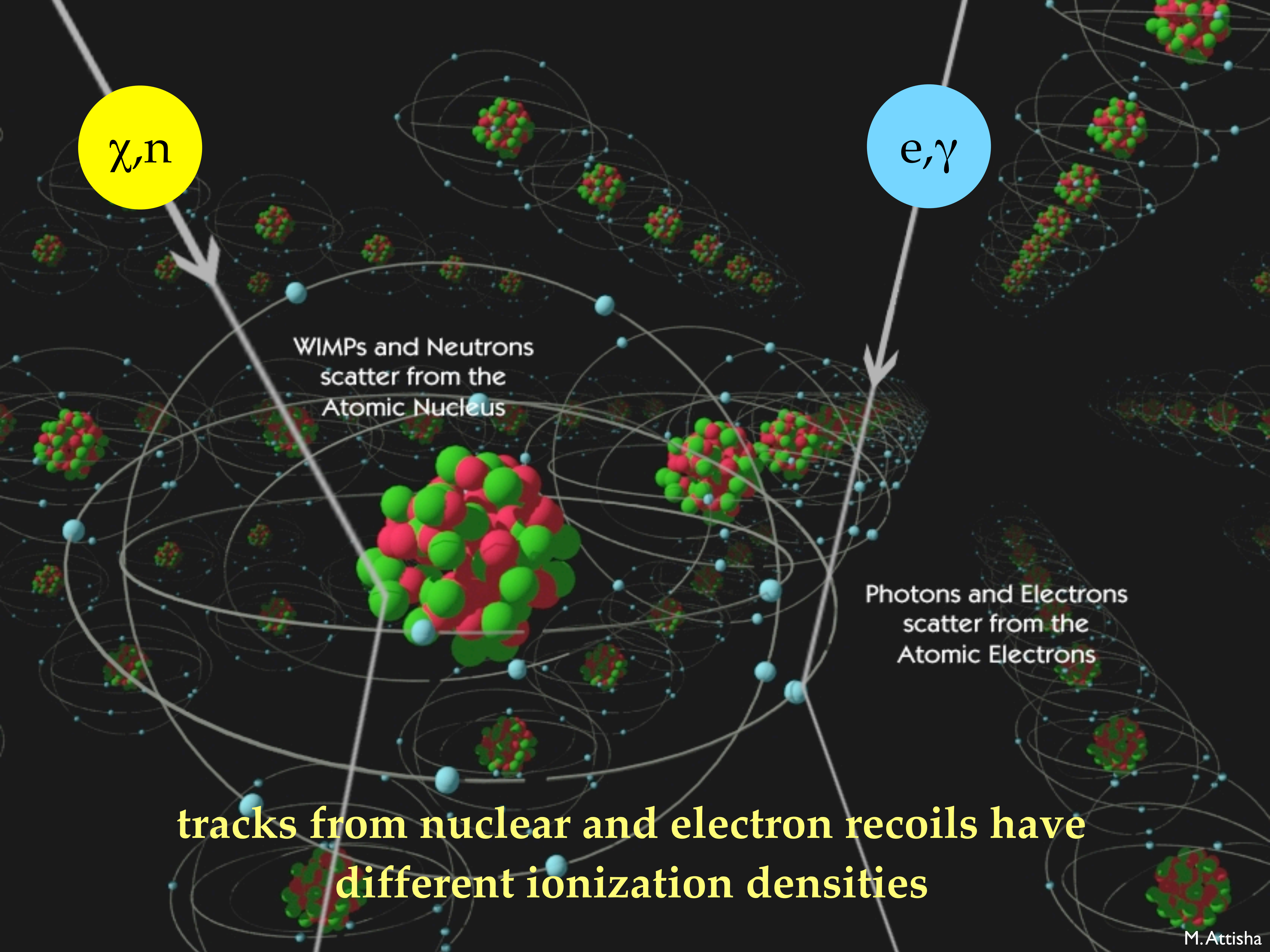
the event topology for nuclear recoils is virtually structureless, and the signals are very low energy

it is very important to handle backgrounds, *i.e.* to be able to say that the signal you see is from WIMPs

low background might not suffice anymore

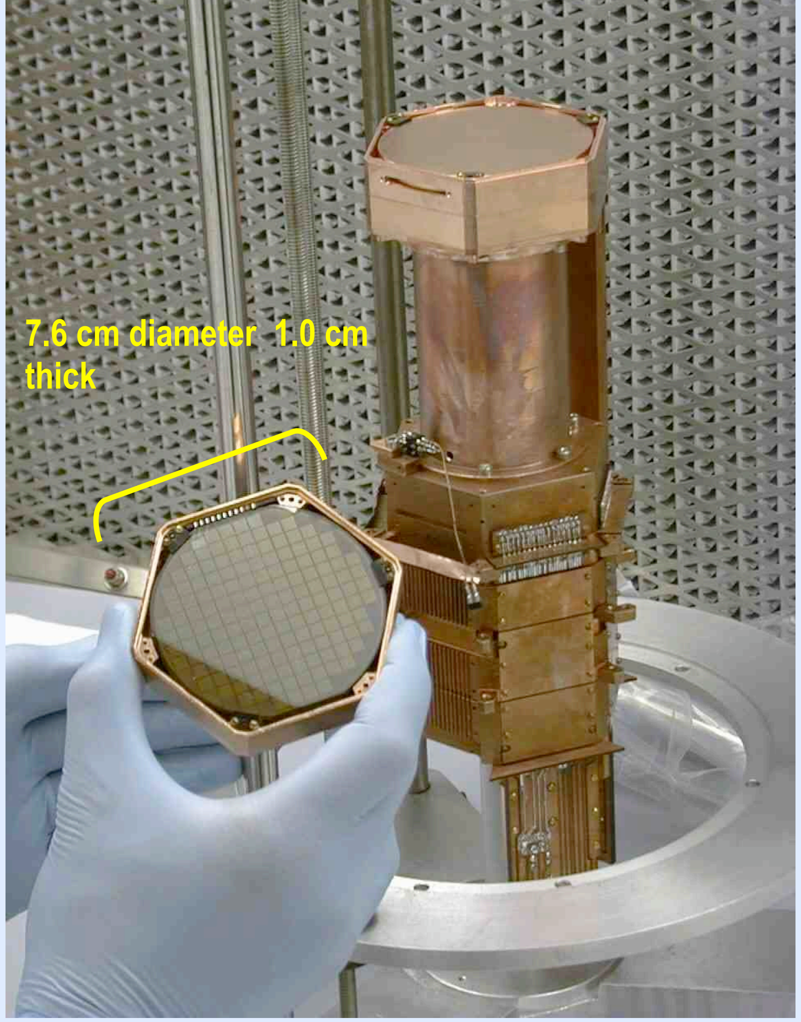
need to aim for a **zero background** window for physics

discrimination
between nuclear and electron (alpha) recoils is key to success

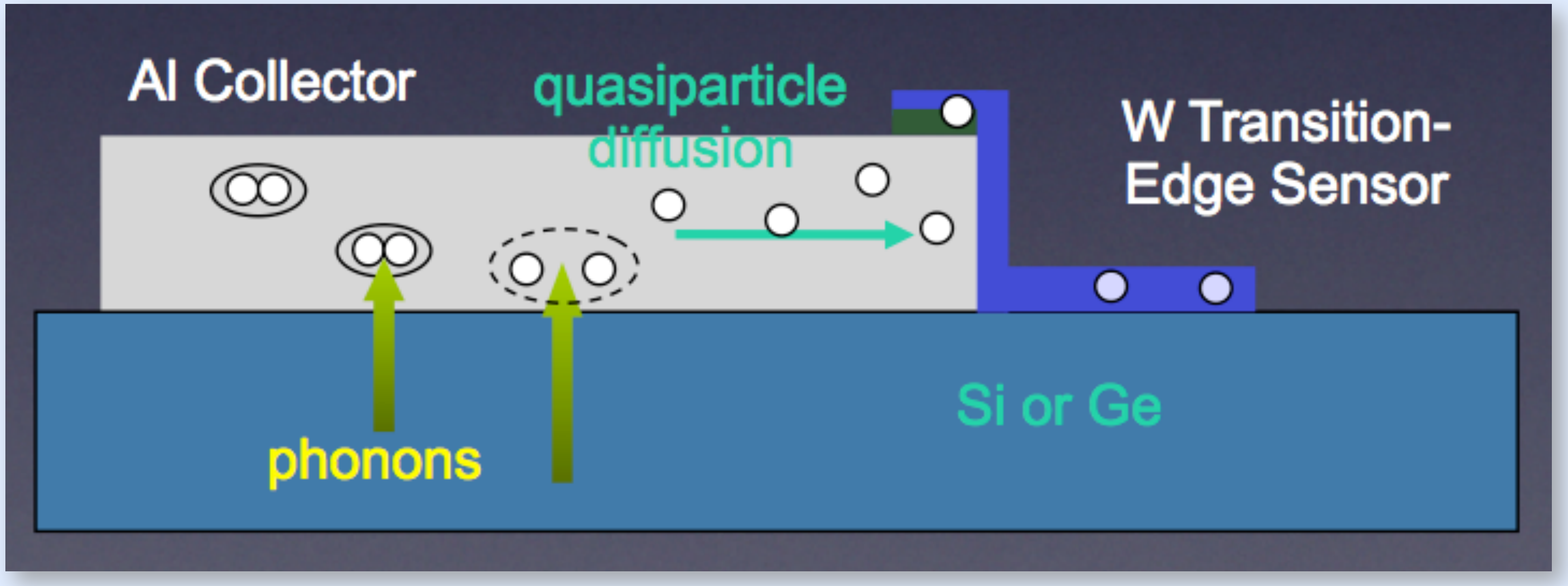


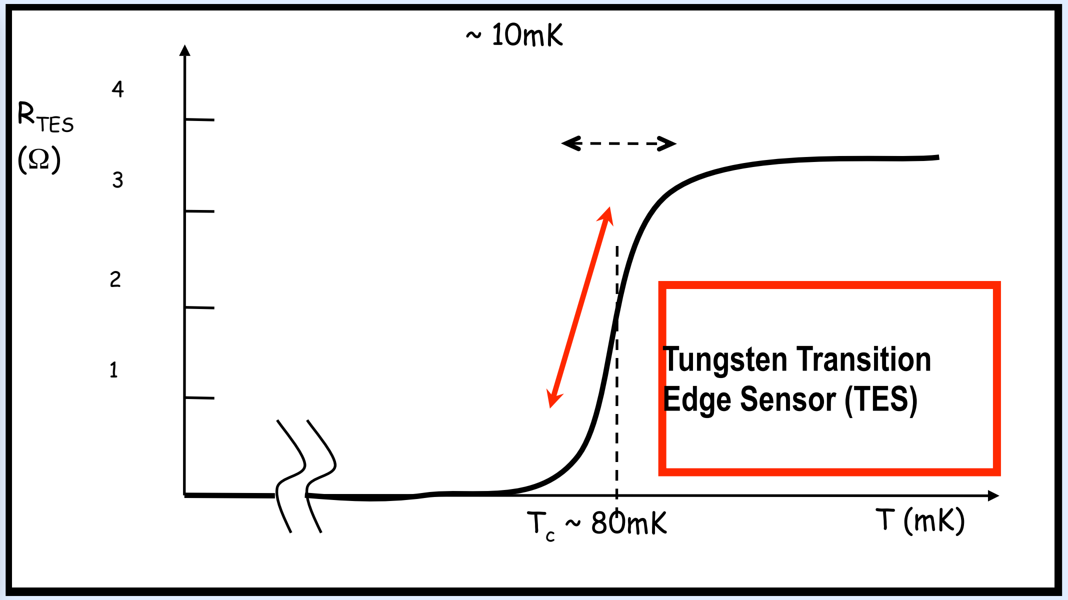
tracks from nuclear and electron recoils have different ionization densities

Cryogenic Dark Matter Search (CDMS): a leader in the field for many years



- deep underground (Soudan mine, Minnesota)
- 5 towers of 6 detectors (some Ge, some Si) @ <50 mK
- ionization ('standard' semiconductor technology)
- phonon read out (TES patterned detectors)





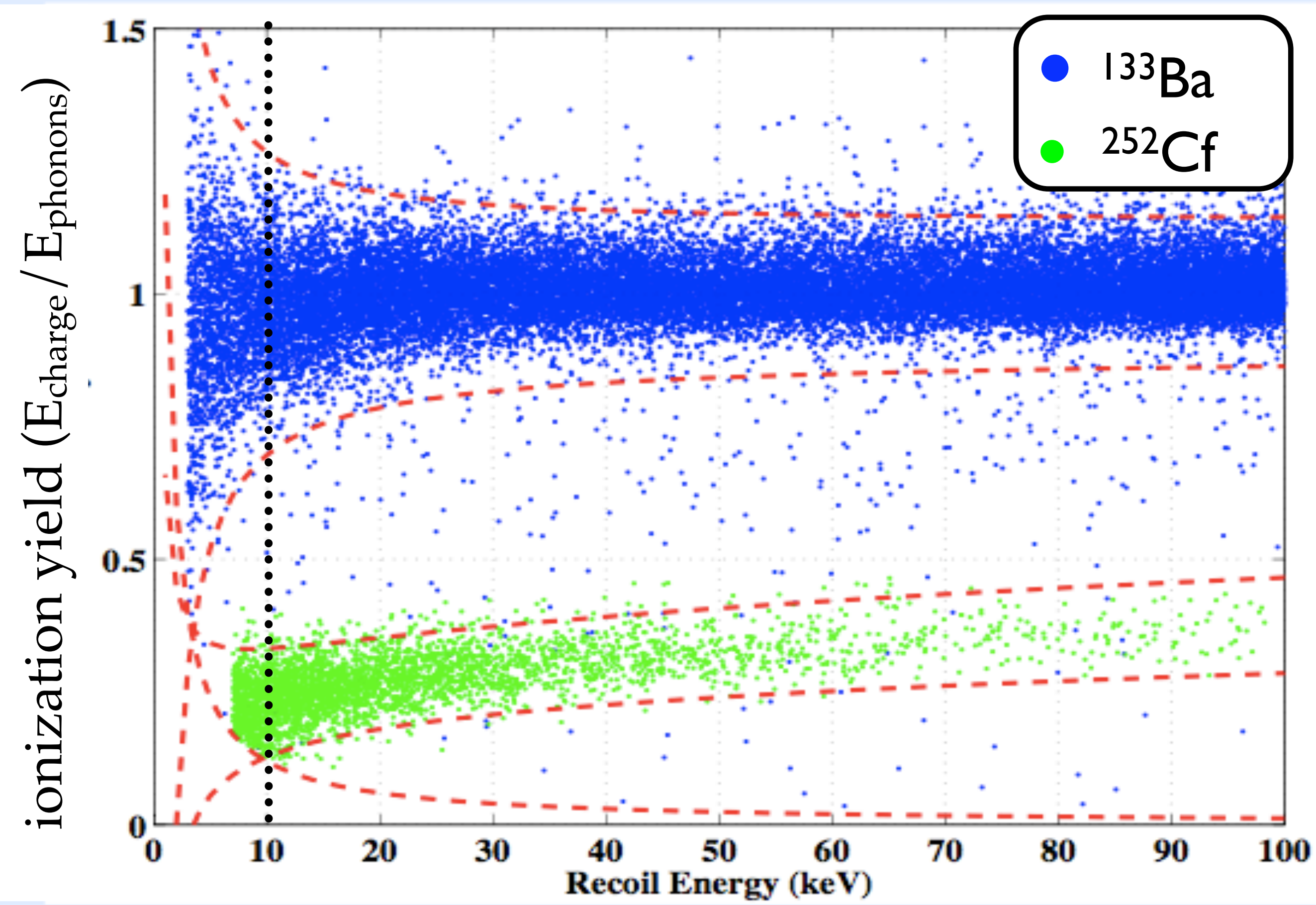
the combined readout provides excellent discrimination power against electron-like events

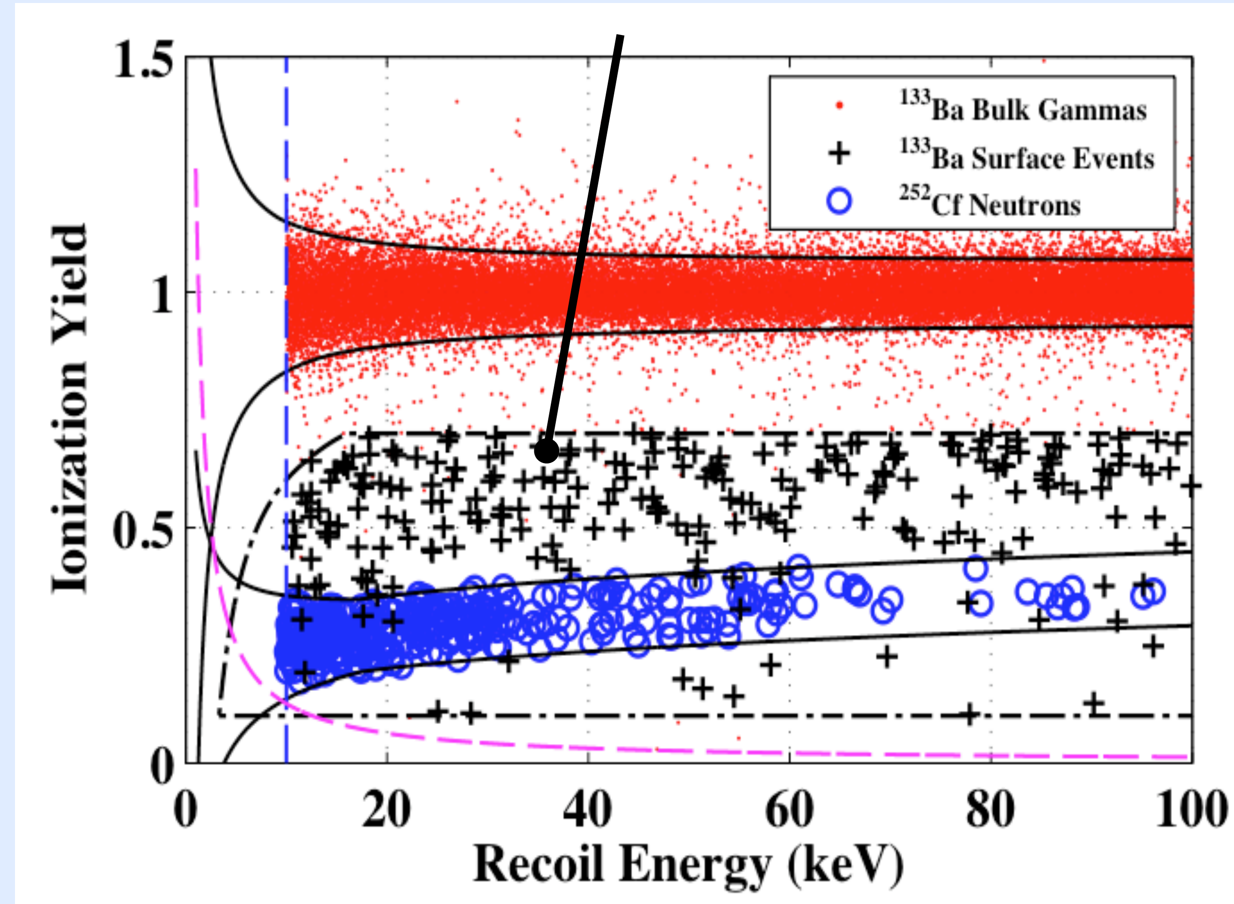
[courtesy: Dan Bauer]

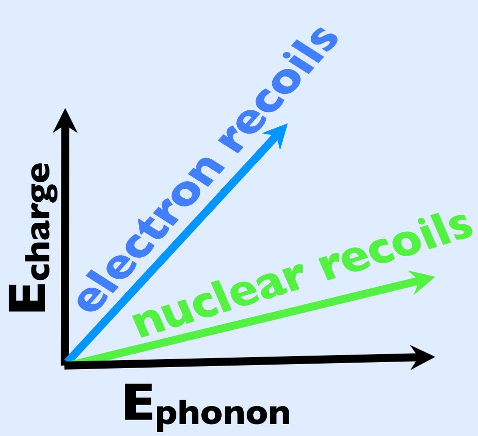
CDMS: event discrimination

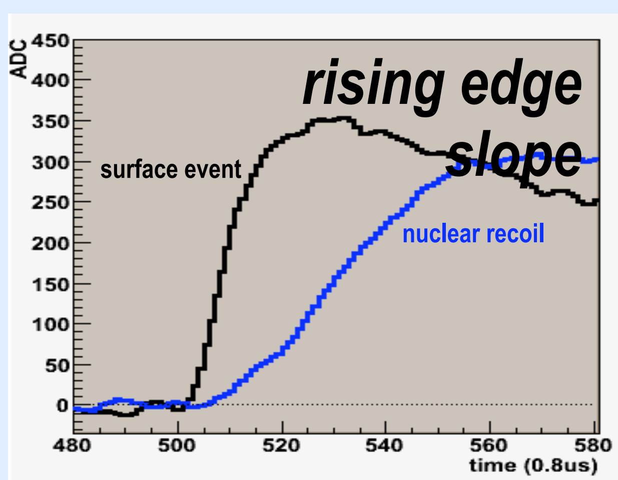
10 μm "dead layer" results in reduced ionization collection

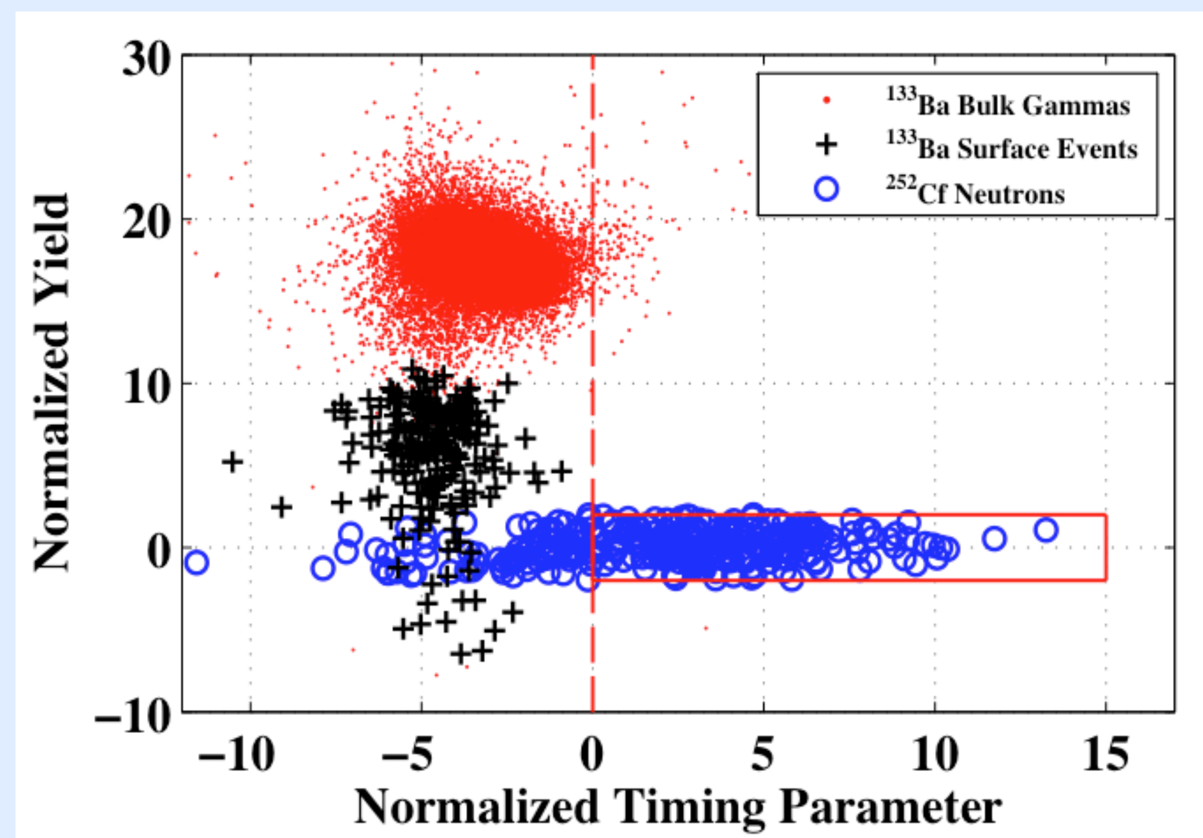
bettern than 1:10^4 rejection









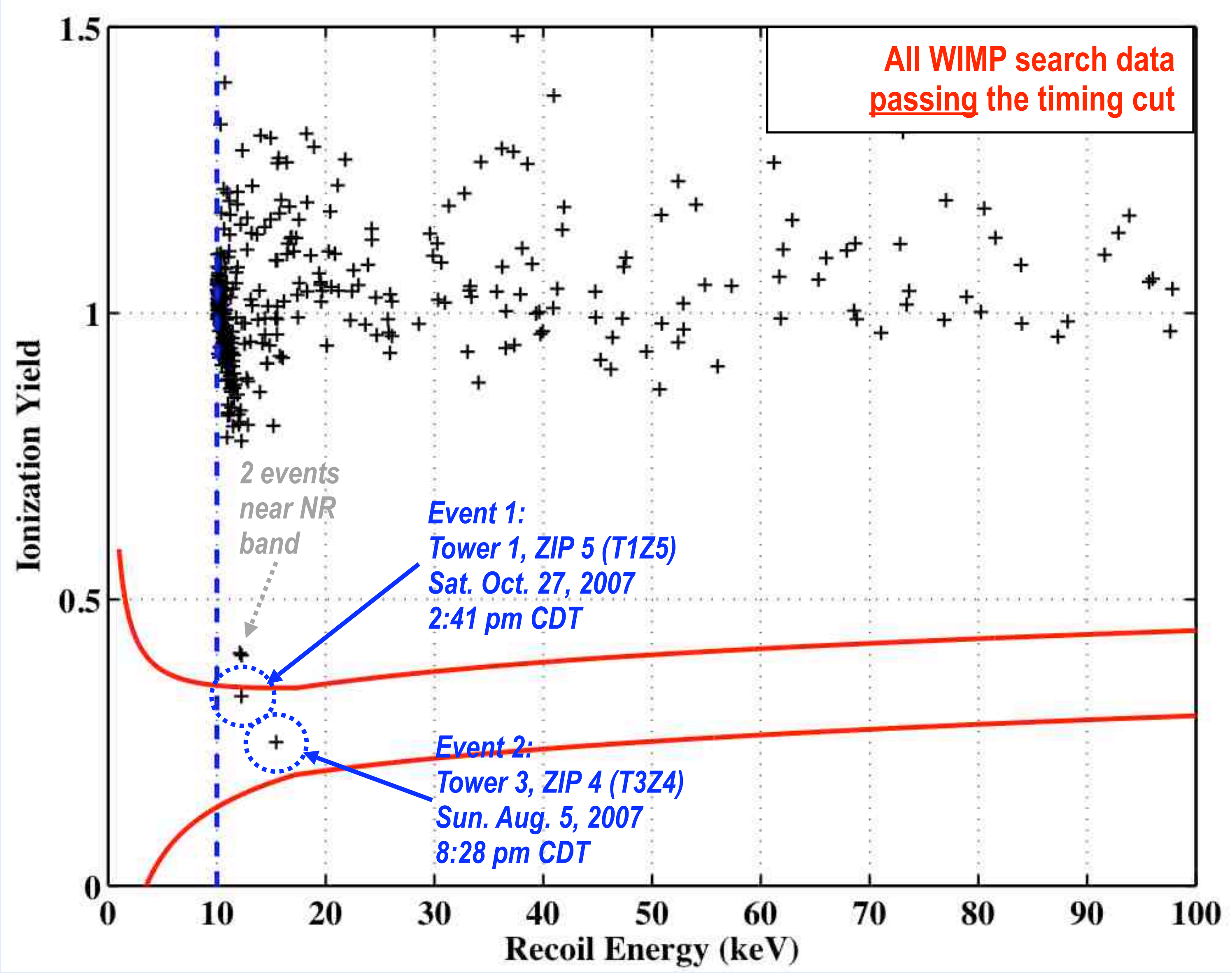


[courtesy: Dan Bauer]

CDMS: latest results

[arXiv:0912.3592]

- several years (tot exposure)
- extensive calibration
- ionization yield
- pulse rise time analysis
- extensive simulation and evaluation of background expected rates (neutron, surface)
- reconstruction and threshold studies
- blind analysis



- 0.8 ± 0.1 (stat) ± 0.2 (syst) surface events expected
- ~0.1 neutron events expected

→

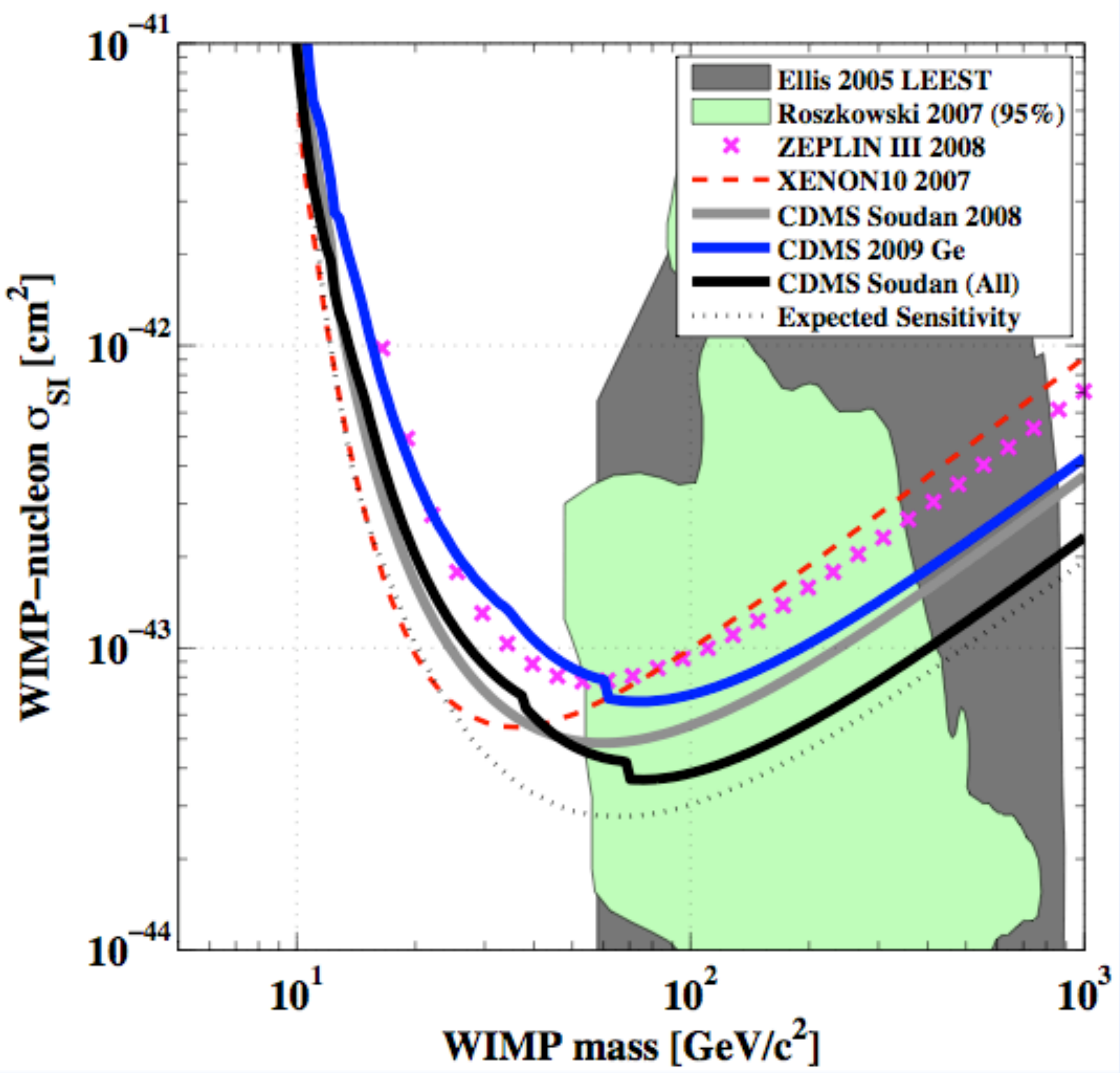
2 events in the nuclear recoil band pass the timing cut (23% probability)

no definitive WIMP claim possible

[courtesy: Dan Bauer]

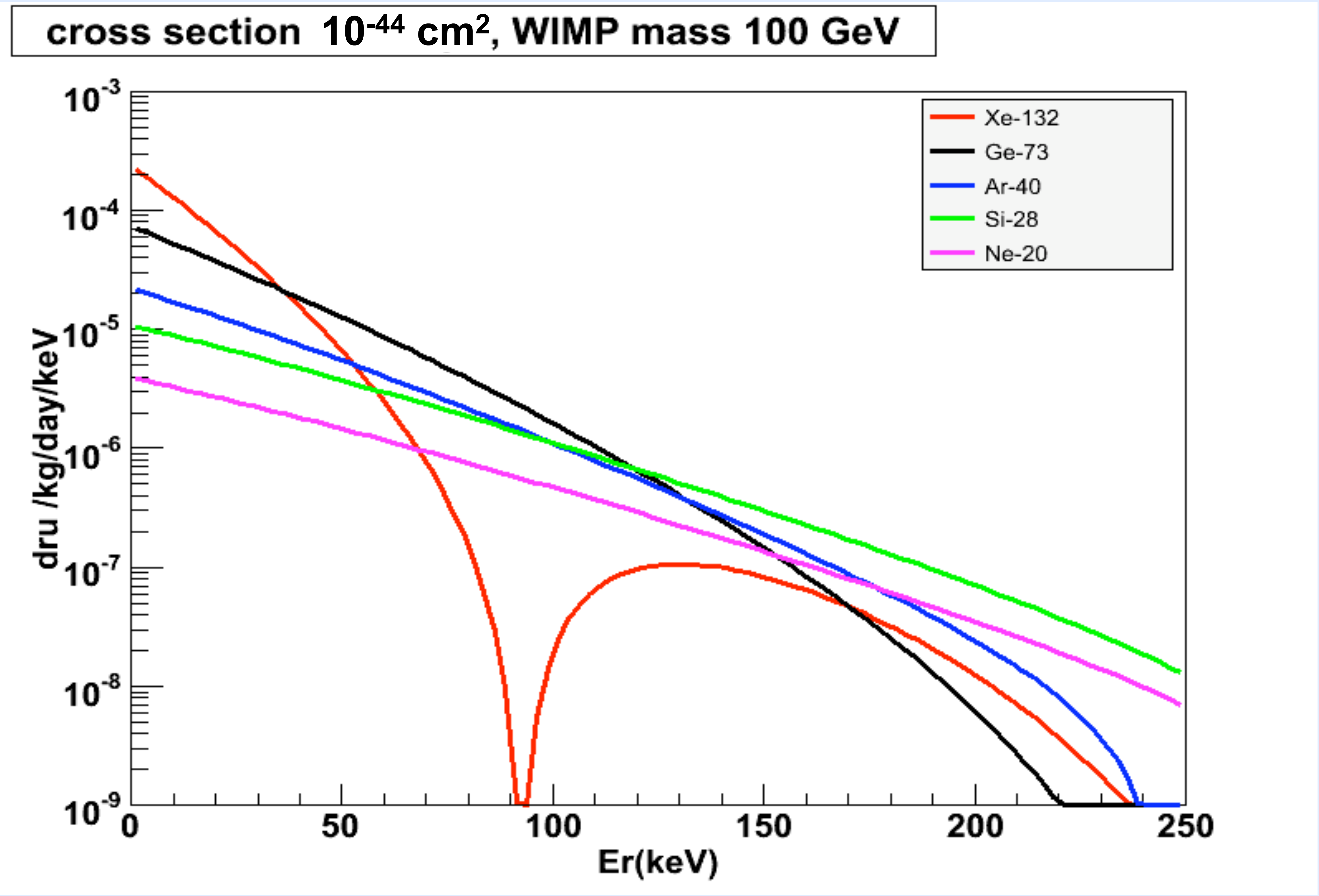
WIMP sensitivity plots

- use standard assumptions on the Milky Way dark matter halo
- sensitivity is highly dependent on WIMP mass
- sensitivity decreases rapidly if WIMP mass << target mass
- if he detected events are zero or compatible with expected backgrounds a upper limit on the cross section can be set
- the expected sensitivity is based on a zero background scenario



[courtesy: Dan Bauer]

target mass dependance of WIMP cross section



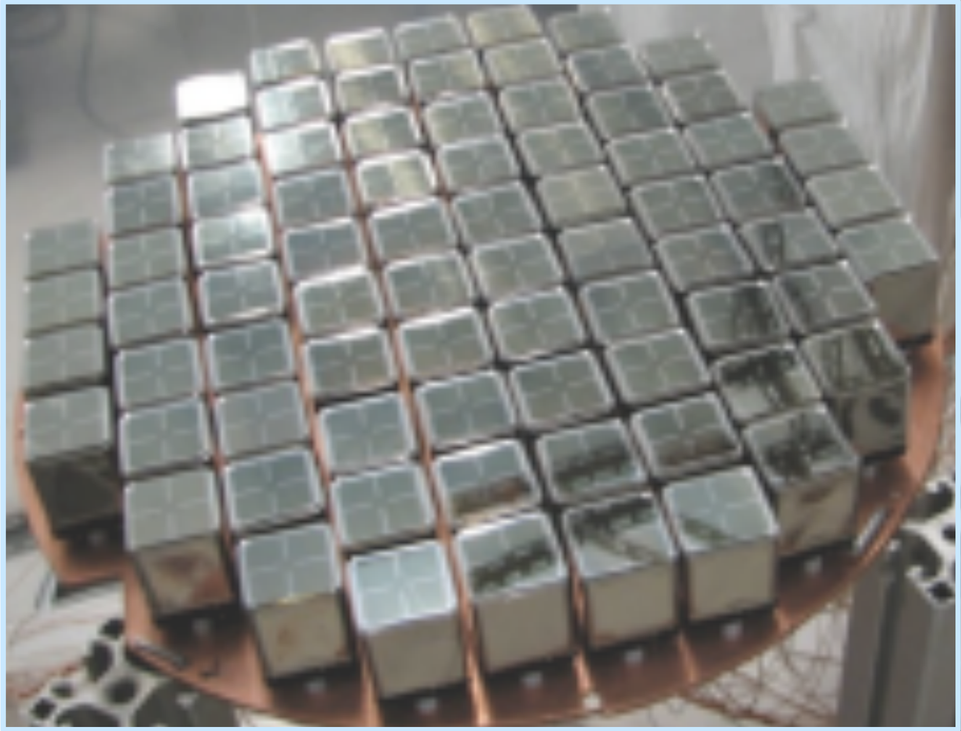
[courtesy: Katsushi Arisaka]

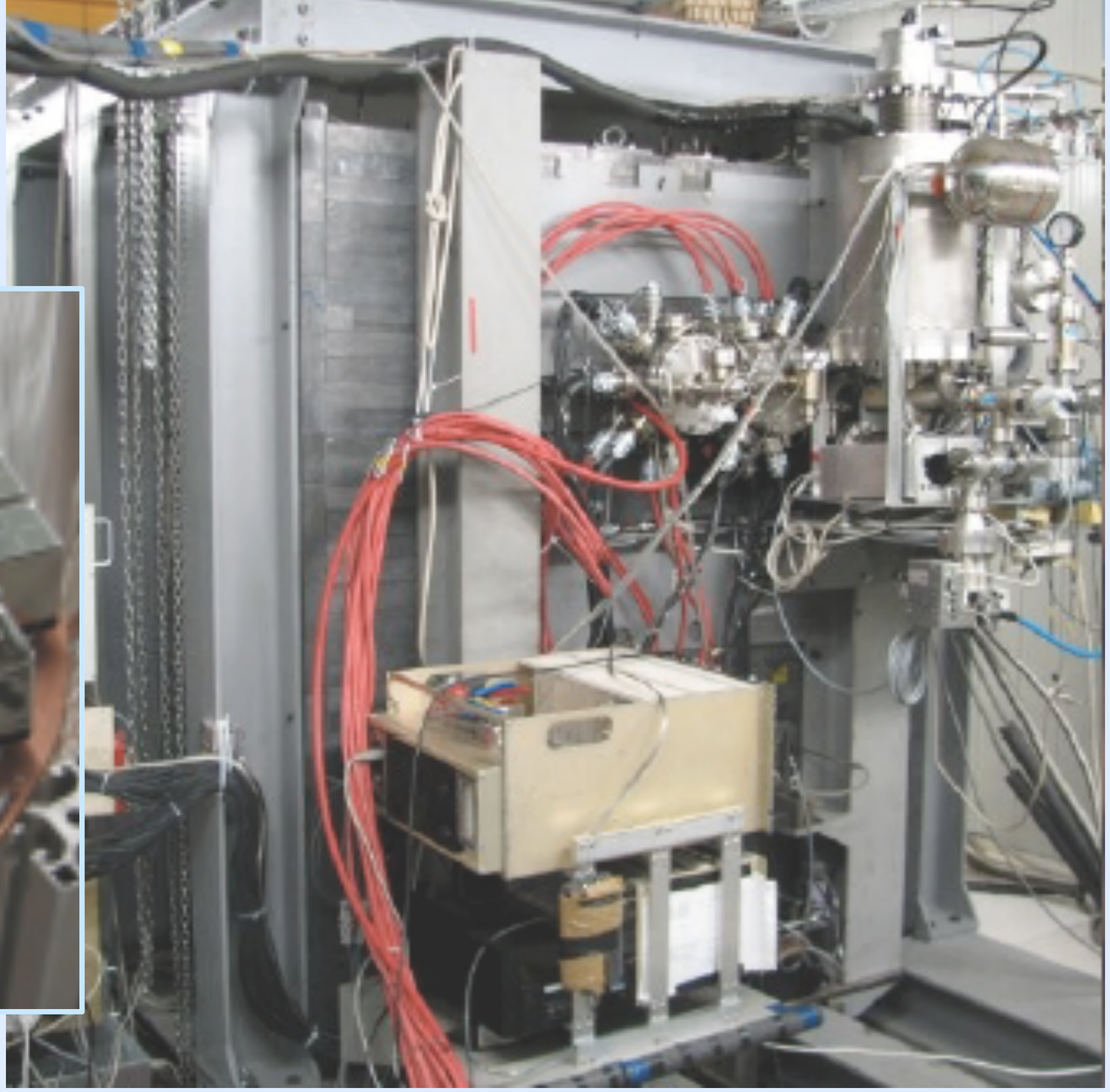
noble liquid detectors: rapidly growing competitors

- Target = Detector
- 3D position reconstruction
- Excellent scintillation detectors: 40 photons/keV (Ar, 128 nm), 46 photons/keV (Xe, 178 nm)
- Excellent ionization detectors: 40 electrons/keV (Ar), 64 electrons/keV (Xe)
- Photons and electrons not self-absorbed
- Easily purified
- Good/excellent background discrimination
- Good/excellent self-shielding
- Large multi-ton detectors possible and “cheap”

Xe
XENON
Dark Matter Project

XENON 100

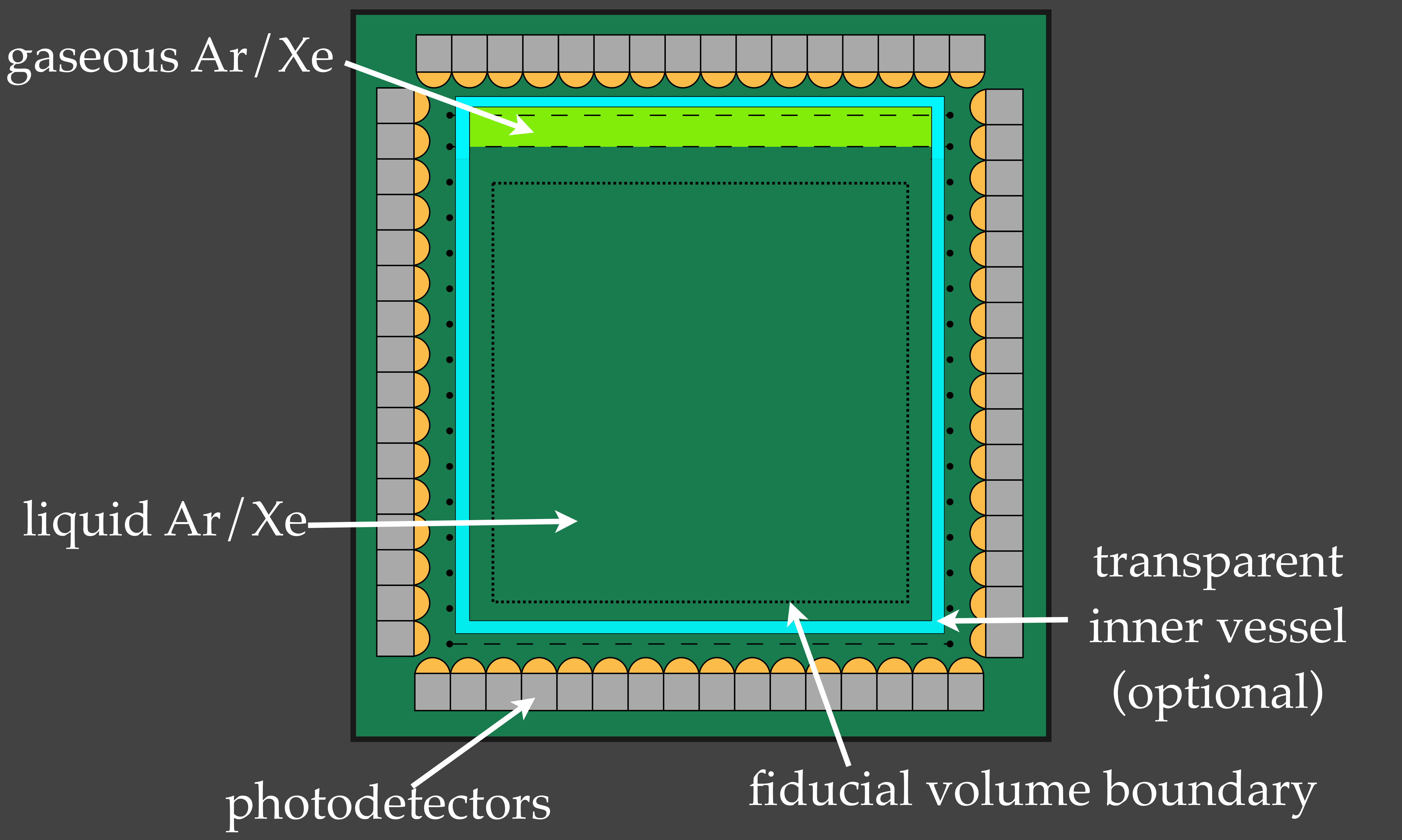




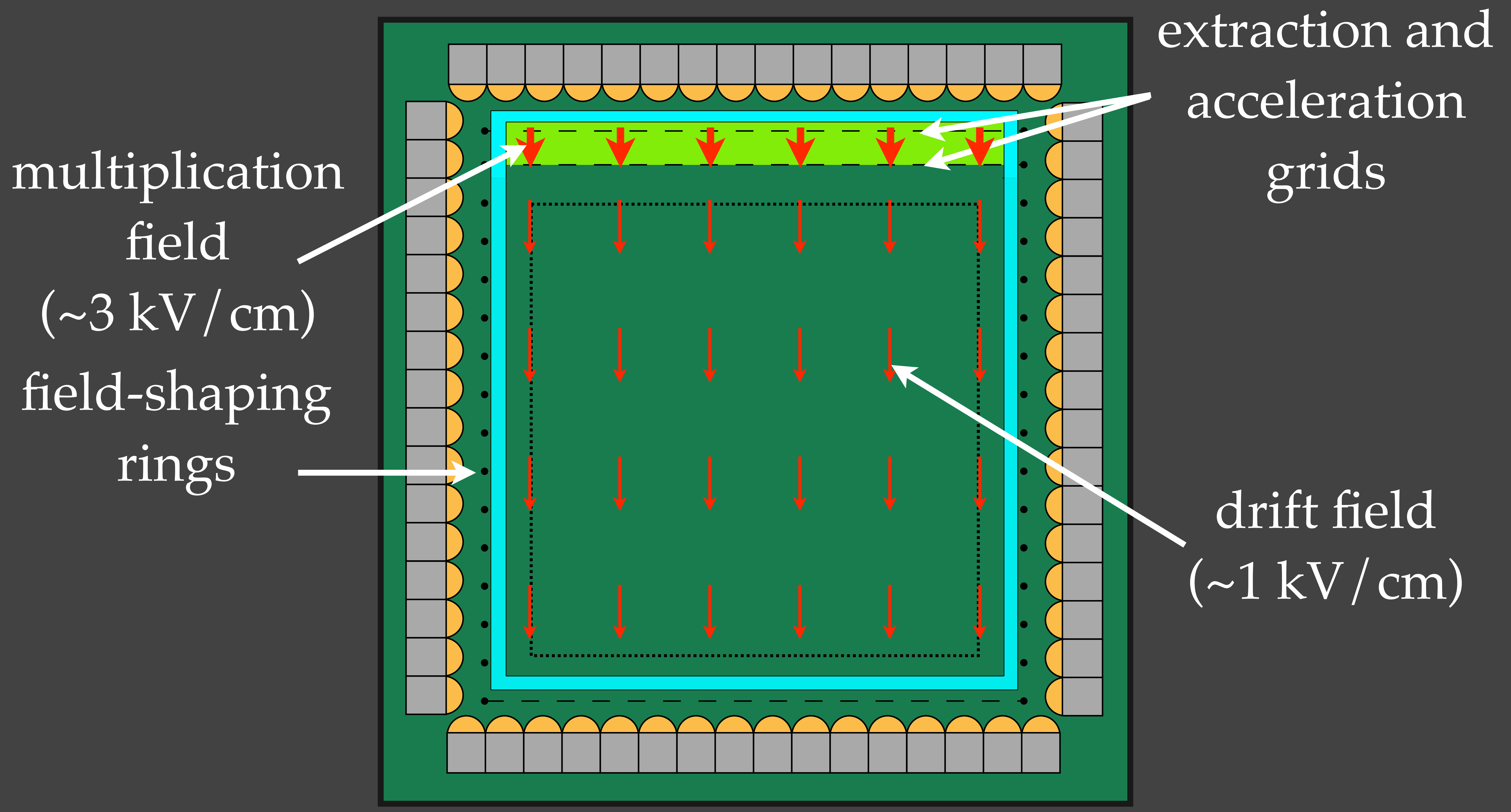
- 2-phase liquid xenon time projection chamber (TPC) at Gran Sasso
- follows successful XENON 10 experiment
- 61 kg LXe in target volume
- 4 cm-thick active LXe veto for shielding
- 242 1″x1″ low background PMTs
- improved XENON 10 shield (Pb, polyethylene, Cu, water, N_2 purge)

[from: Marc Schumann @ IDM 2010]

2-phase TPC in action

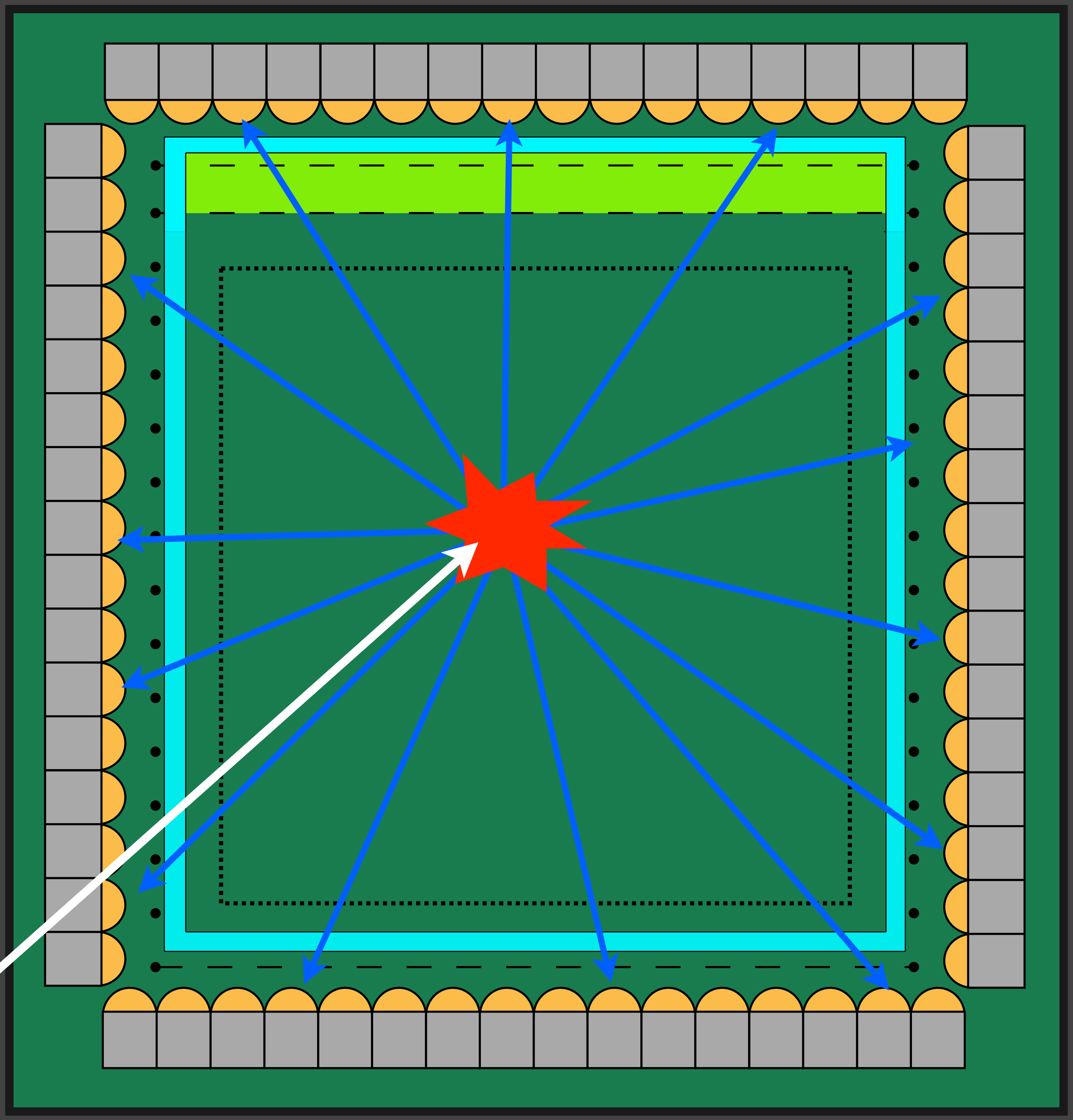


2-phase TPC in action



2-phase TPC in action

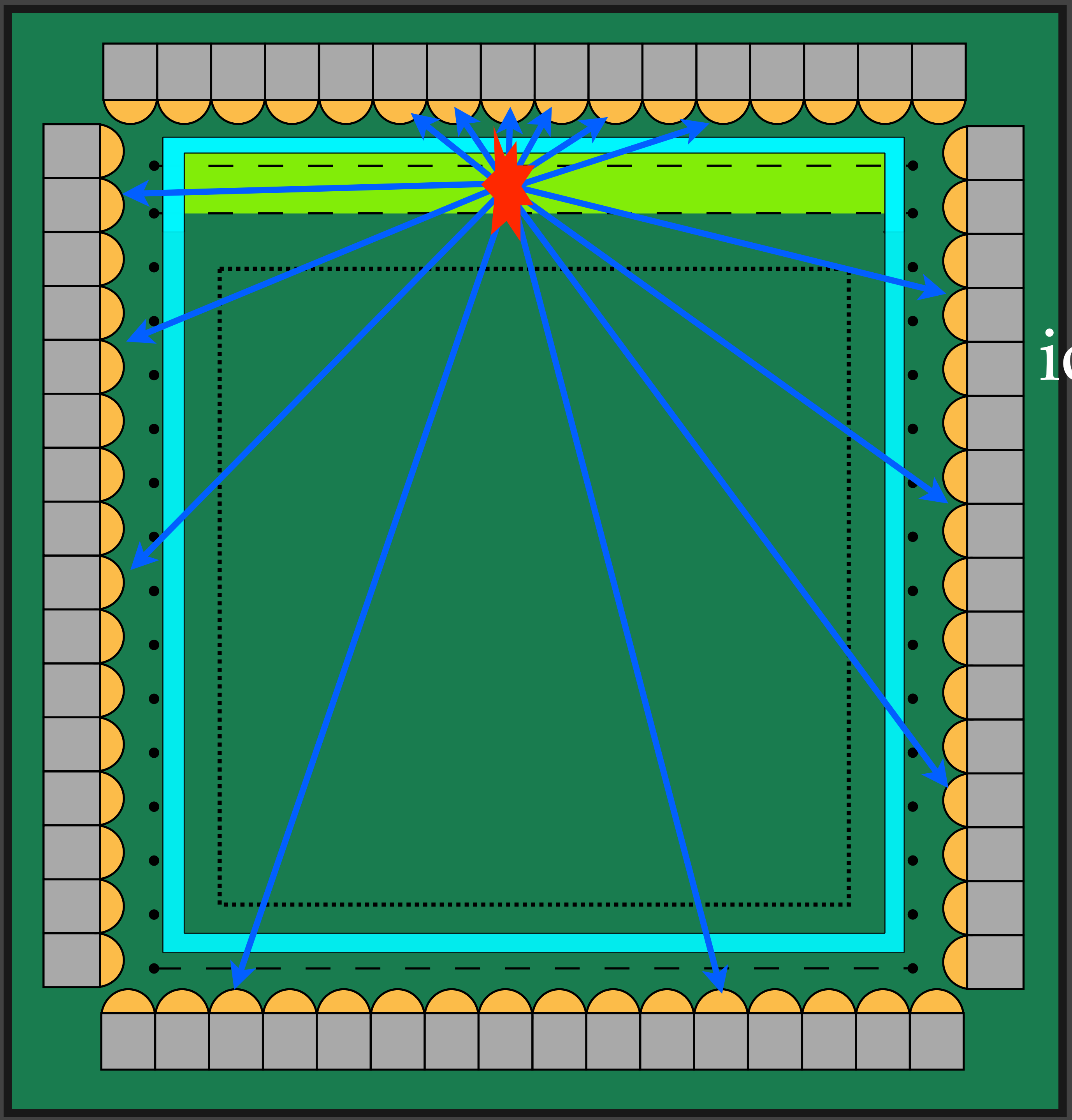
primary scintillation photons
emitted and detected (S1)



WIMP Scatter
deposits
energy in FV

2-phase TPC in action

secondary photons emitted by multiplication in gas region (S2)



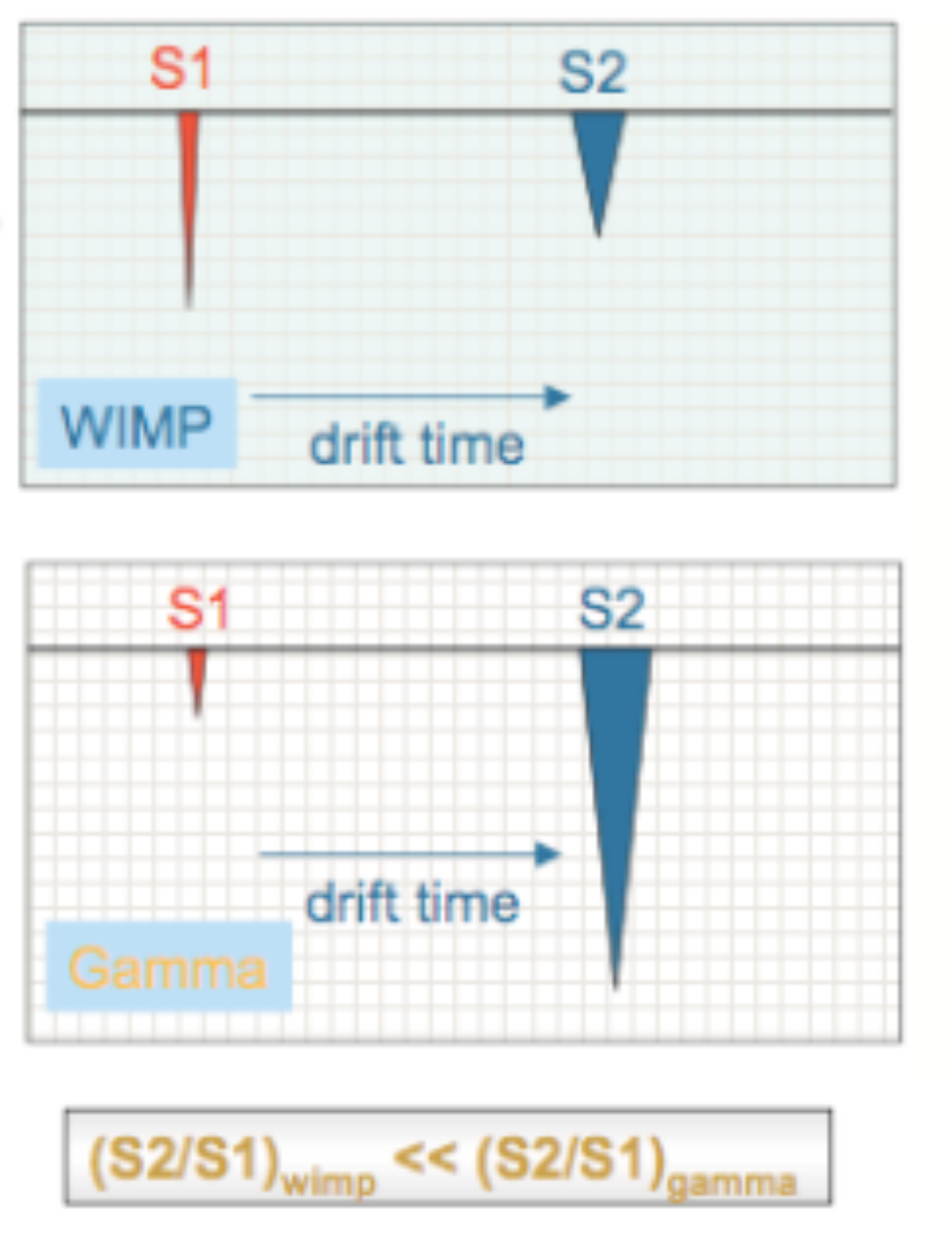
ionized electrons drifted to gas region

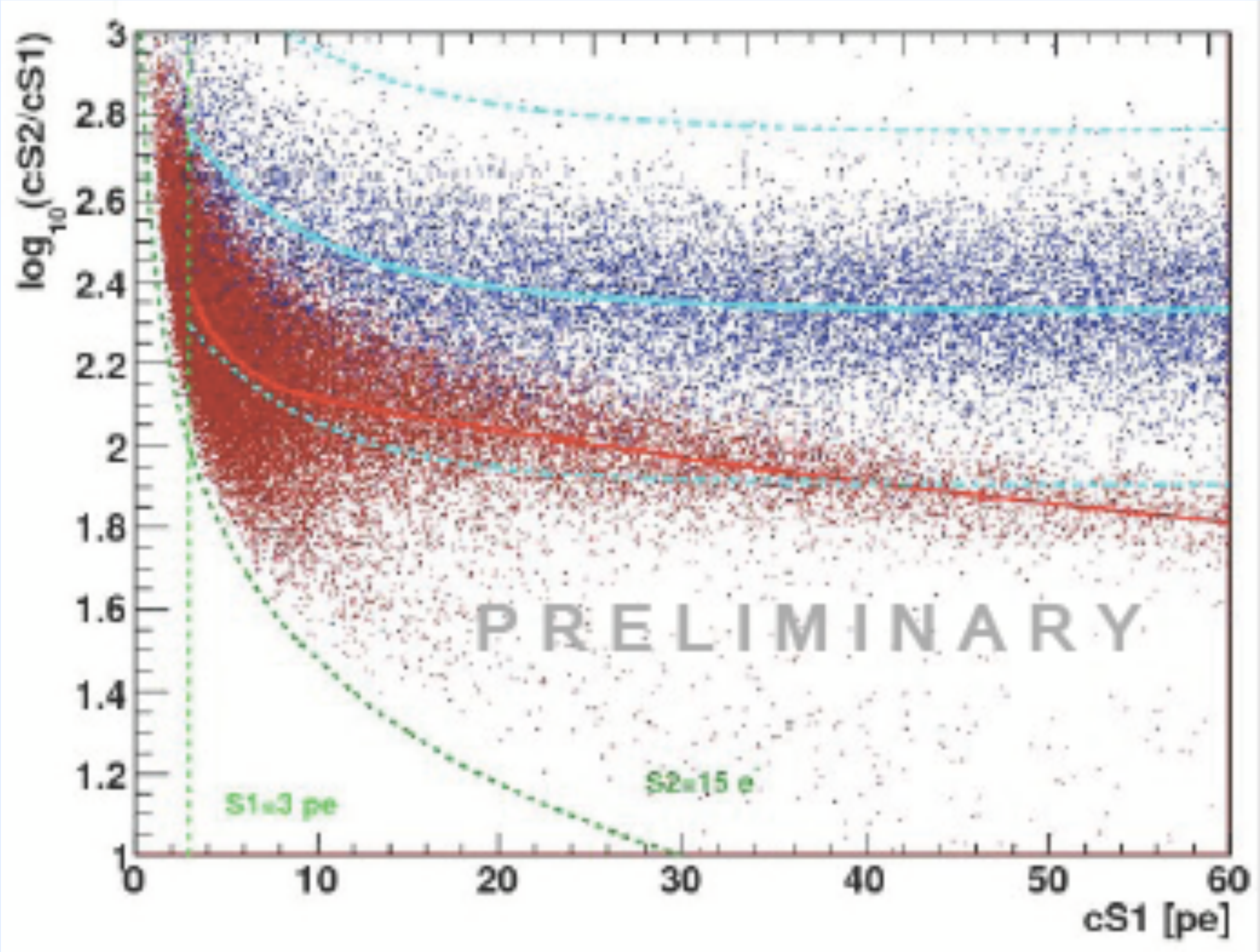
XENON 100: first results

[arXiv:1005.0380]

>99% discrimination between nuclear recoils and electron-like events using S1/S2 ratio

- extensive calibration with sources (^{137}Cs, ^{60}Co, ^{228}Th, ^{57}Co, AmBe)
- ~200 μs drift time, possibly improving over time

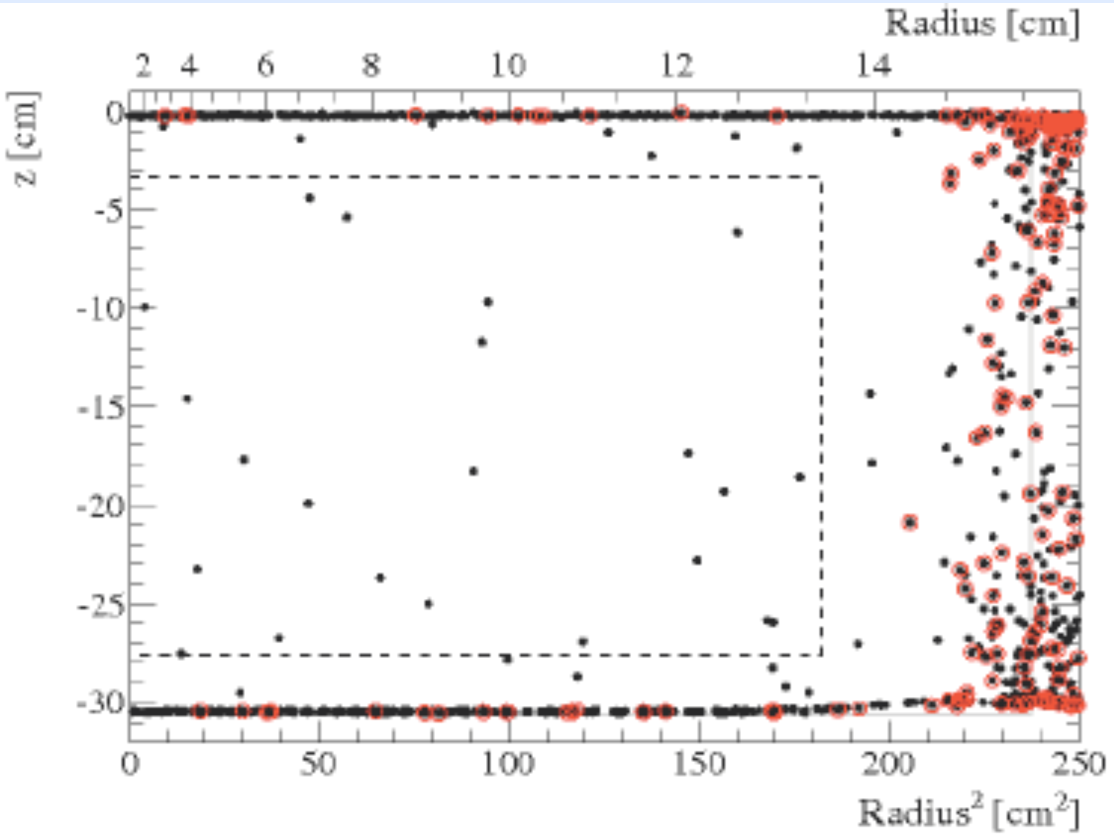




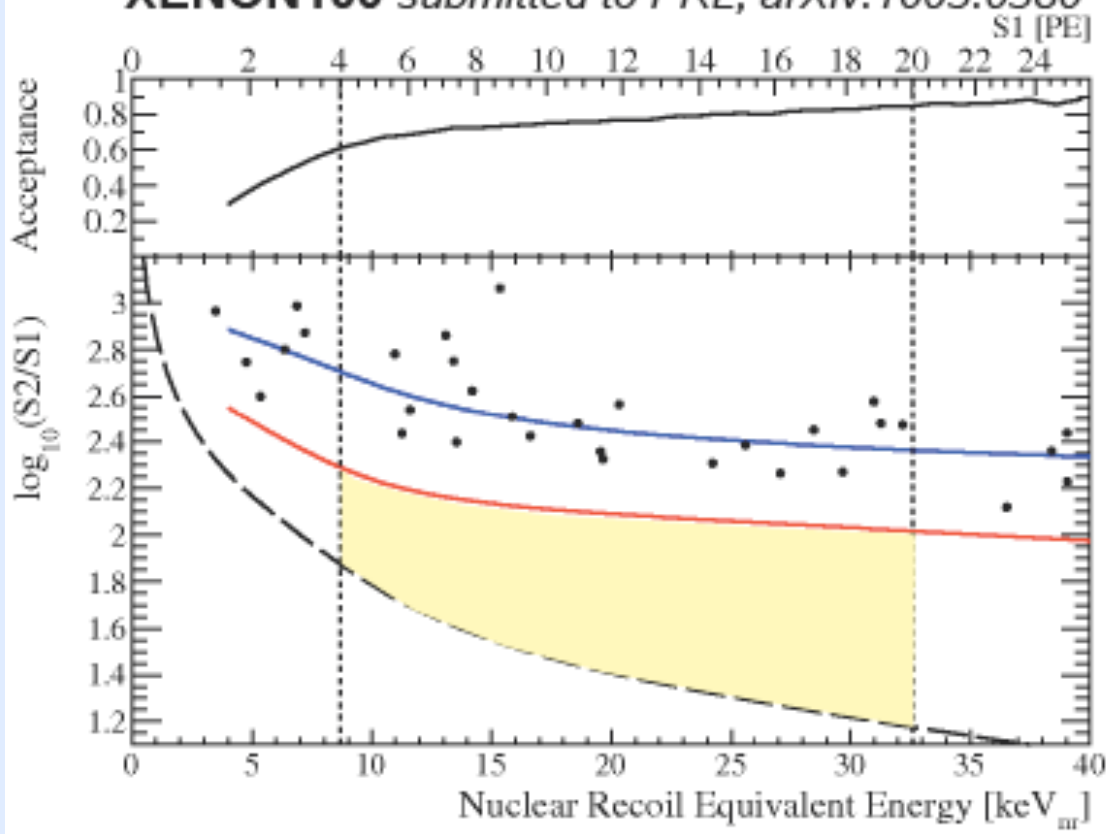
[from: Marc Schumann @ IDM 2010]

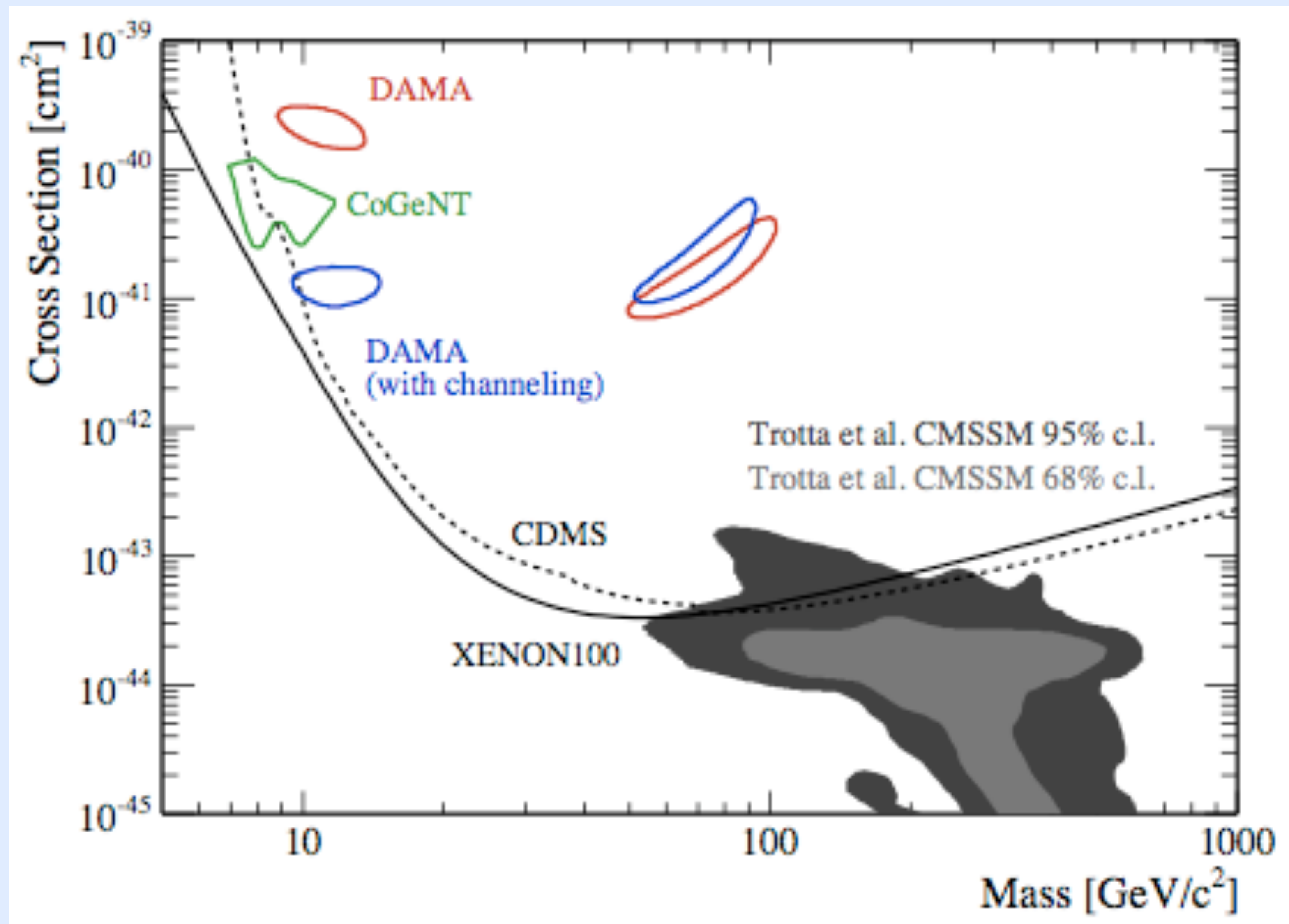
XENON 100: first results

- 11.2 days livetime, 40 kg fiducial mass
- E < 30 keV_{nr}
- background-free after S1/S2 cut
- some controversy over the light yield for low energy nuclear recoils



XENON100 submitted to PRL, arXiv:1005.0380

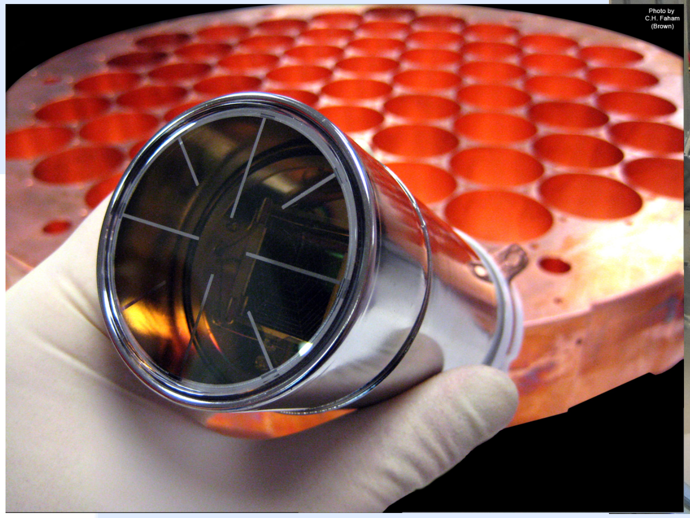


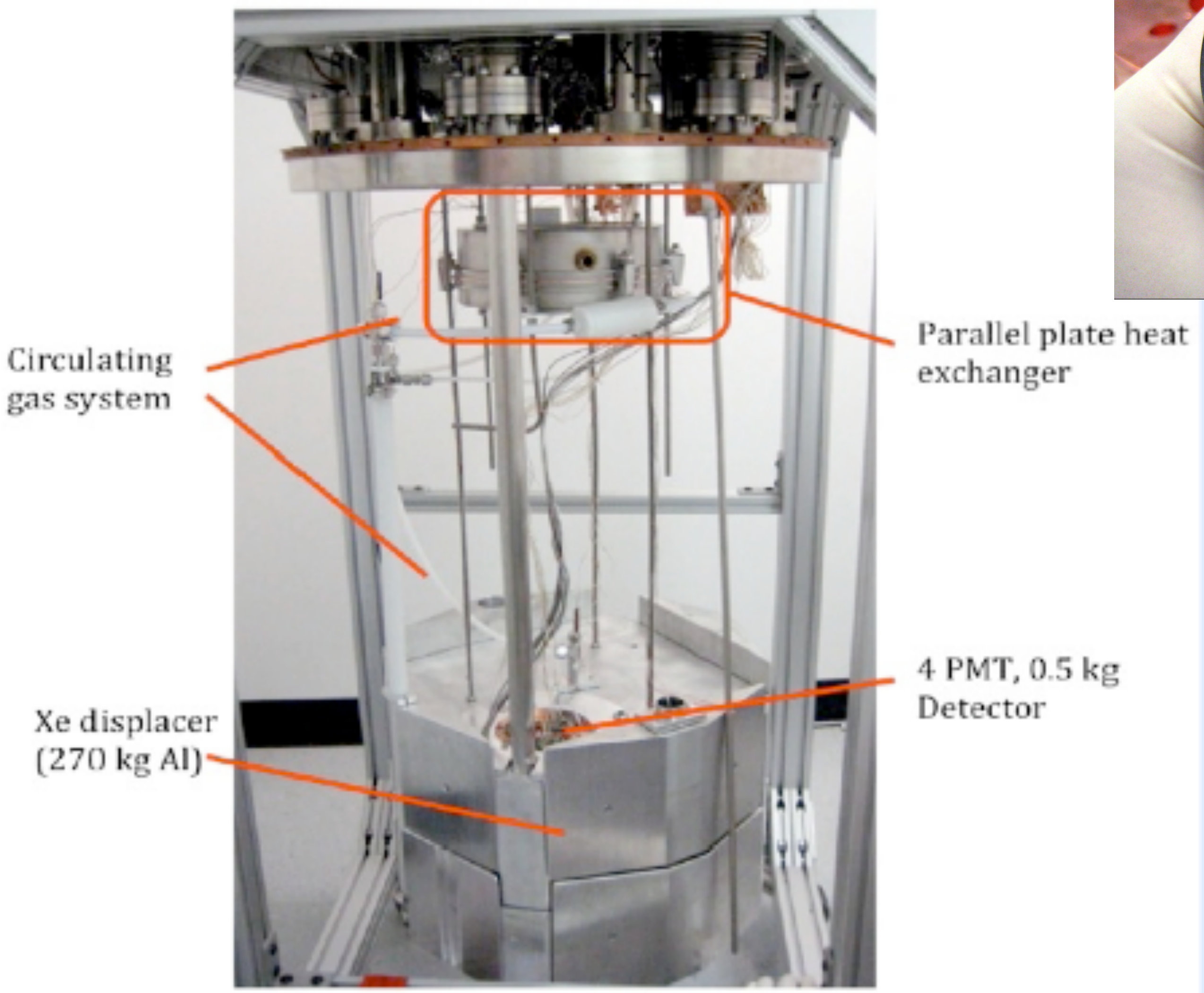


[from: Marc Schumann @ IDM 2010]

the LUX experiment

- 2-phase liquid xenon time projection chamber (TPC) at Homestake (Ray Davis' cavern`)
- split from XENON 10 experiment
- 100 kg LXe fiducial volume
- powerful LXe, active self-shielding
- large water shield



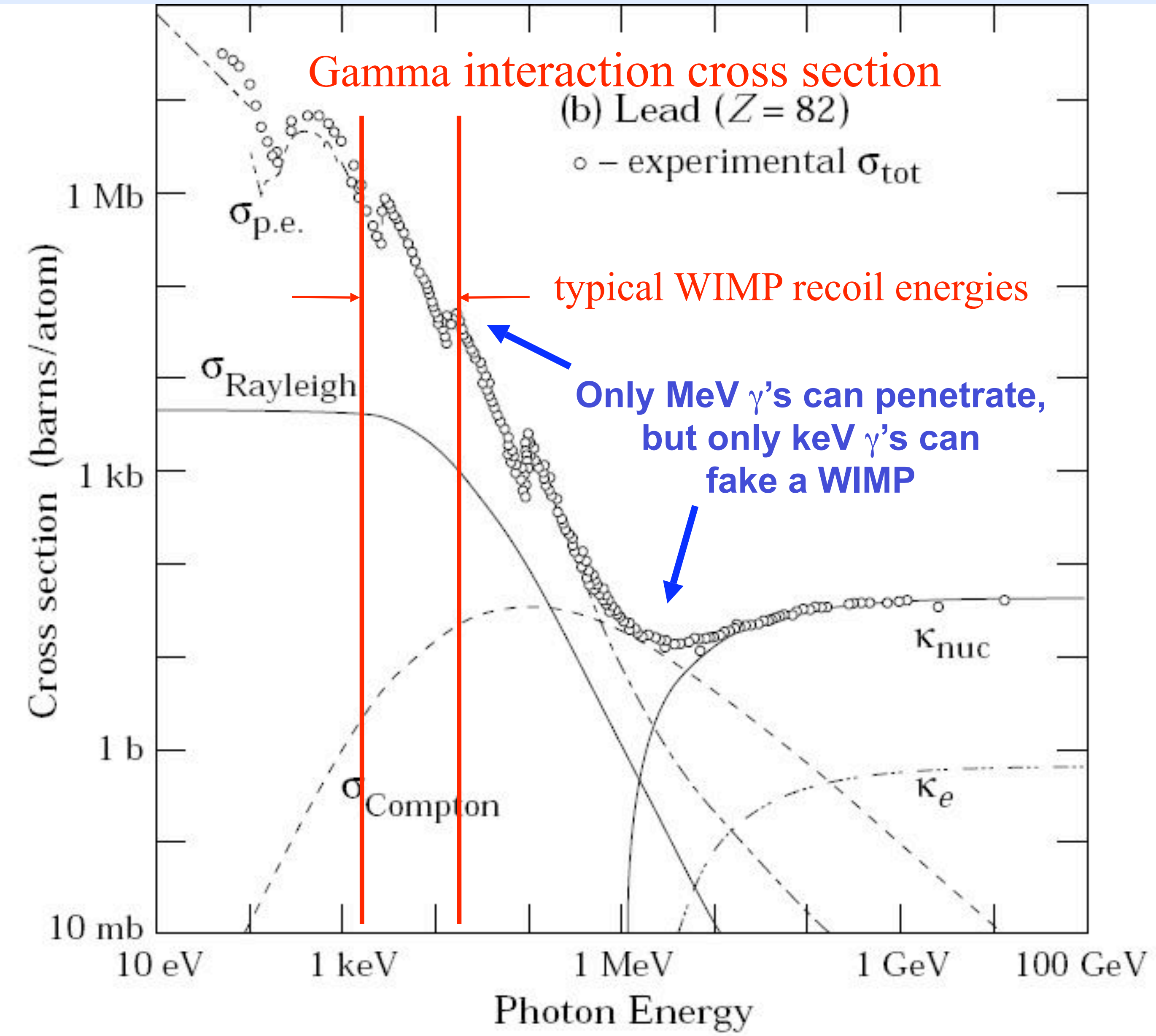


0.2 tons/day recirculated and purified in 60 kg test setup with low power thermal pump

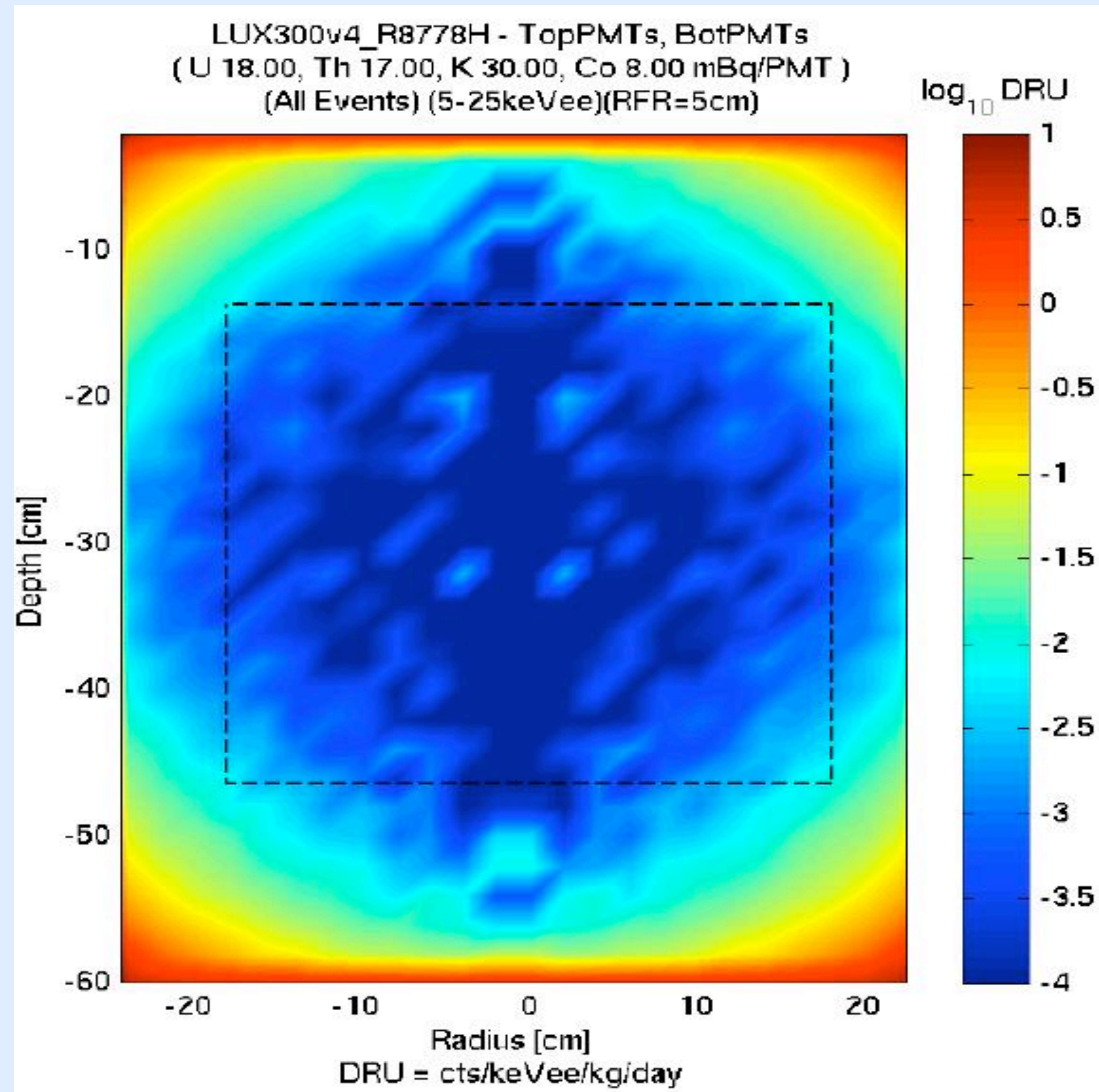
[courtesy: Carter Hall]

Xenon self shielding

it's not hard to shield at 10 keV



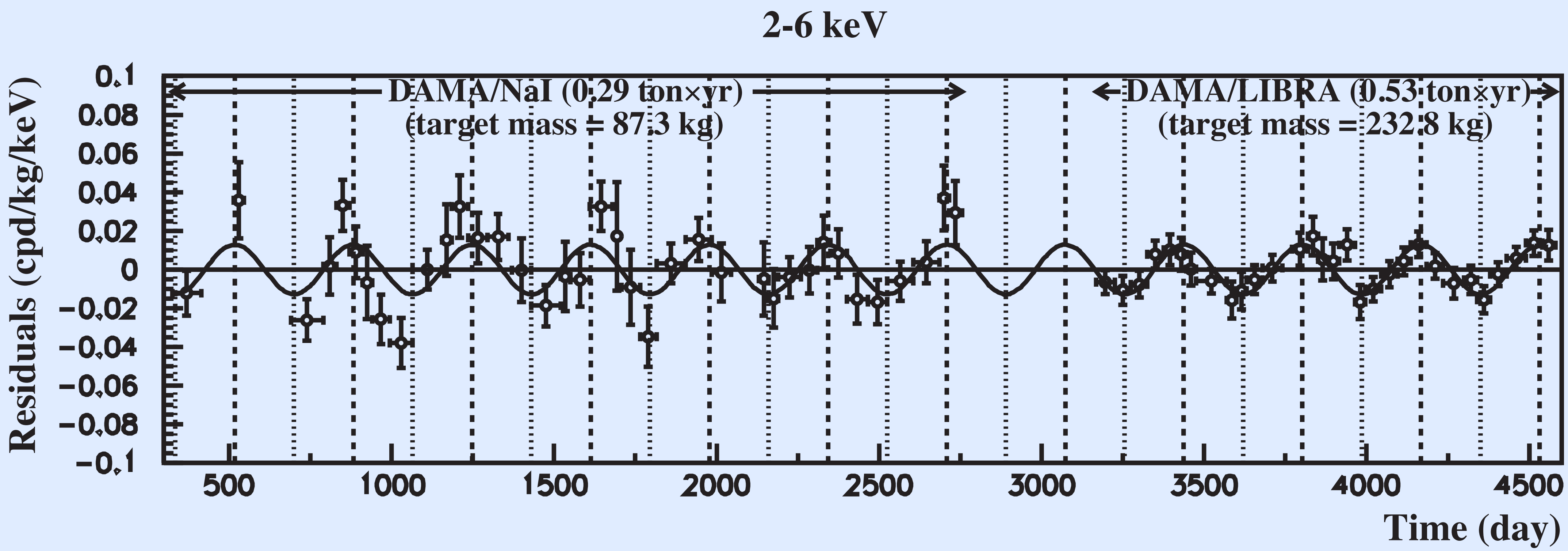
sensitivity improves quickly
as target mass increases



[courtesy: Carter Hall]

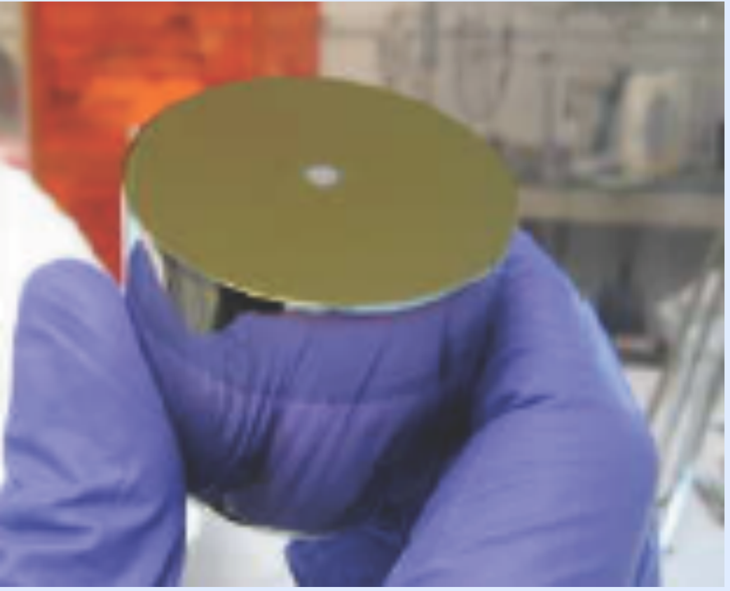
DAMA/LIBRA - positive signal?

- array NaI crystal scintillators, no discrimination, at Gran Sasso
- observed a persistent seasonal variation of low energy 'singles' rate, in phase with the Earth's motion in the hypothetical dark matter halo
- total singles rate ~ 1 cpd/kg; amplitude of oscillation ~ 0.05 cpd/kg



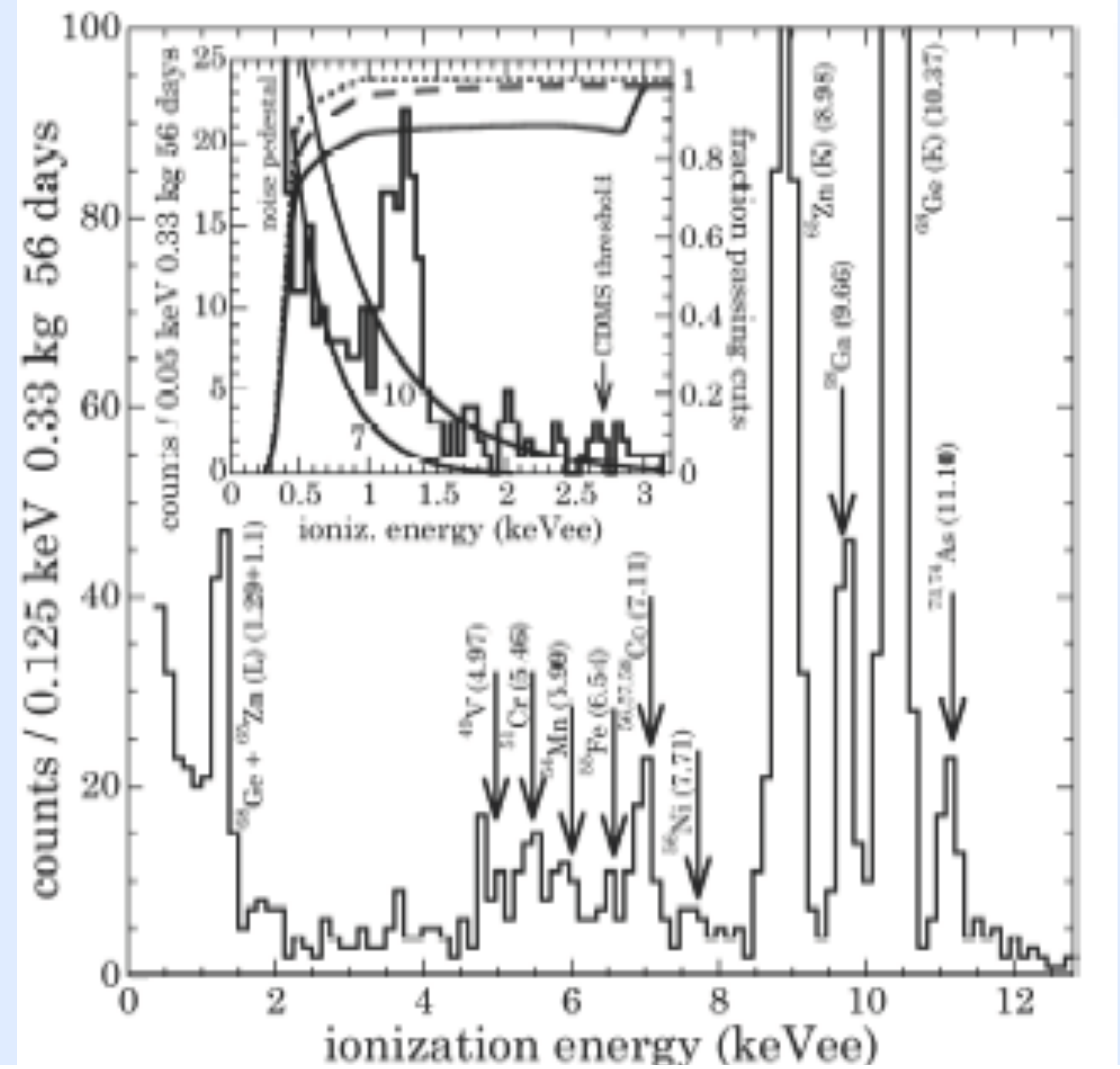
[Eur. Phys. J. C 56, 333 (2008)]

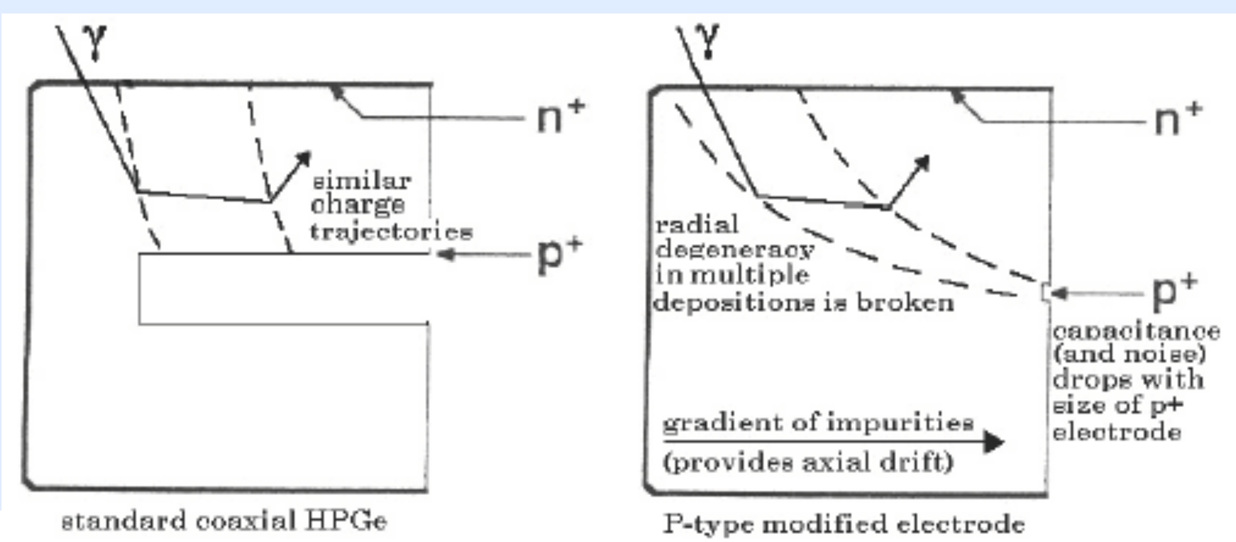
- can be interpreted as spin-independent interaction of light WIMPs (~10 GeV)
- tension with existing experiments (XENON 100 among others)
- has triggered an enormous amount of theoretical and experimental work
- still an open question that needs further investigation



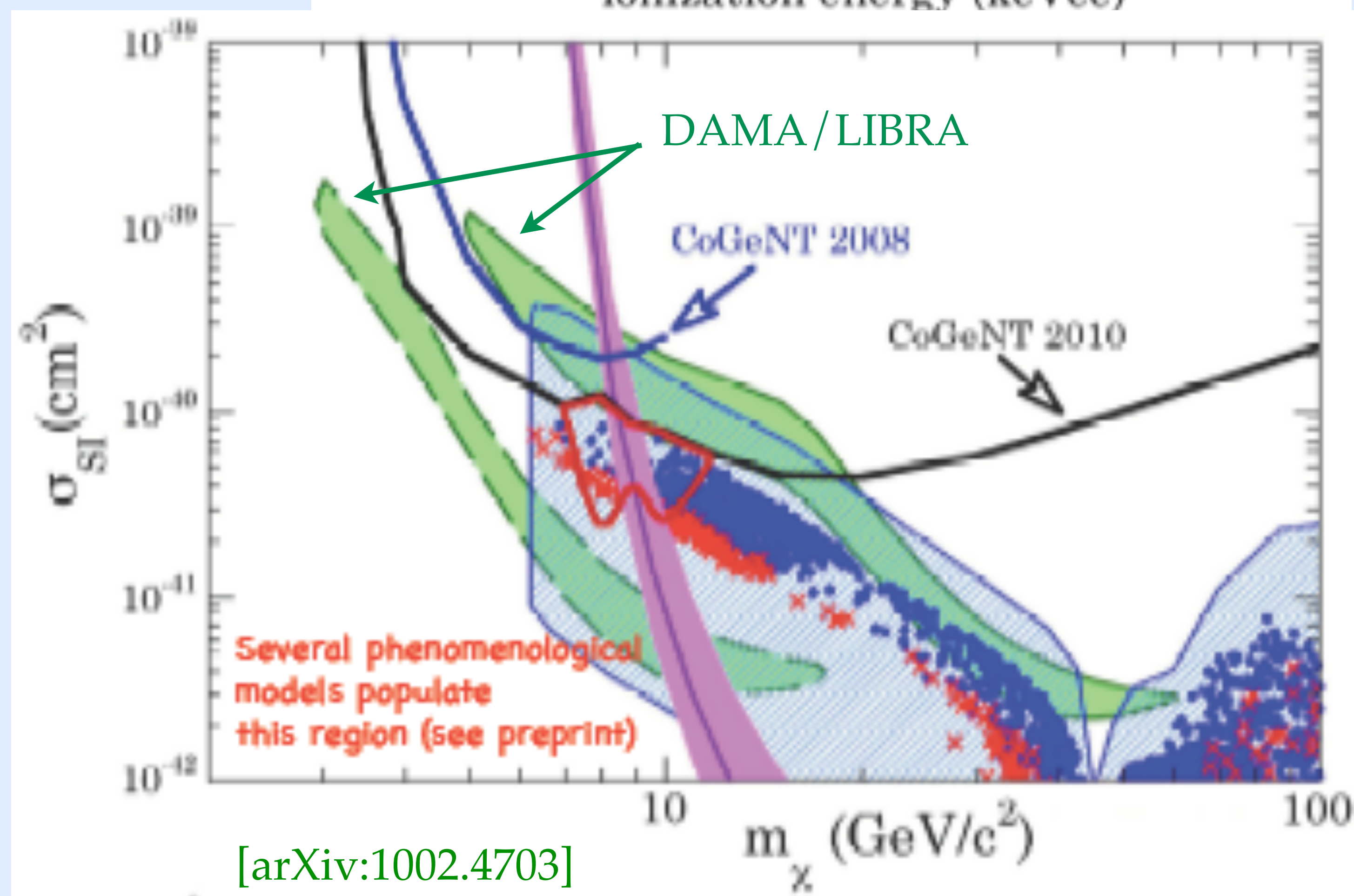
CoGeNT

- p-type point contact (PPC) detectors
- unprecedented low energy threshold
- great energy resolution
- pulse rise time used to reject surface events
- excess of low energy events?
- keep an open mind! (but be cautious)

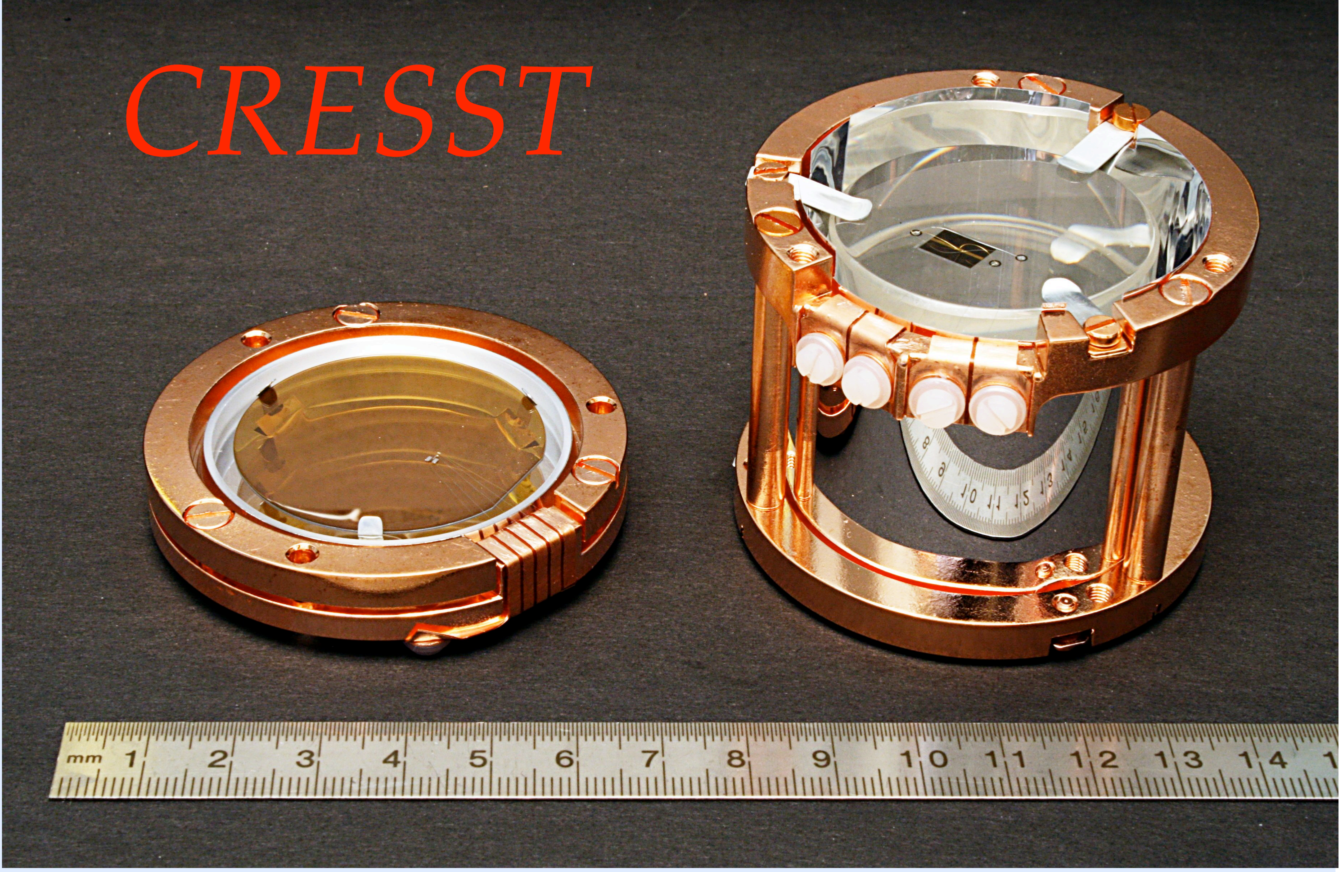


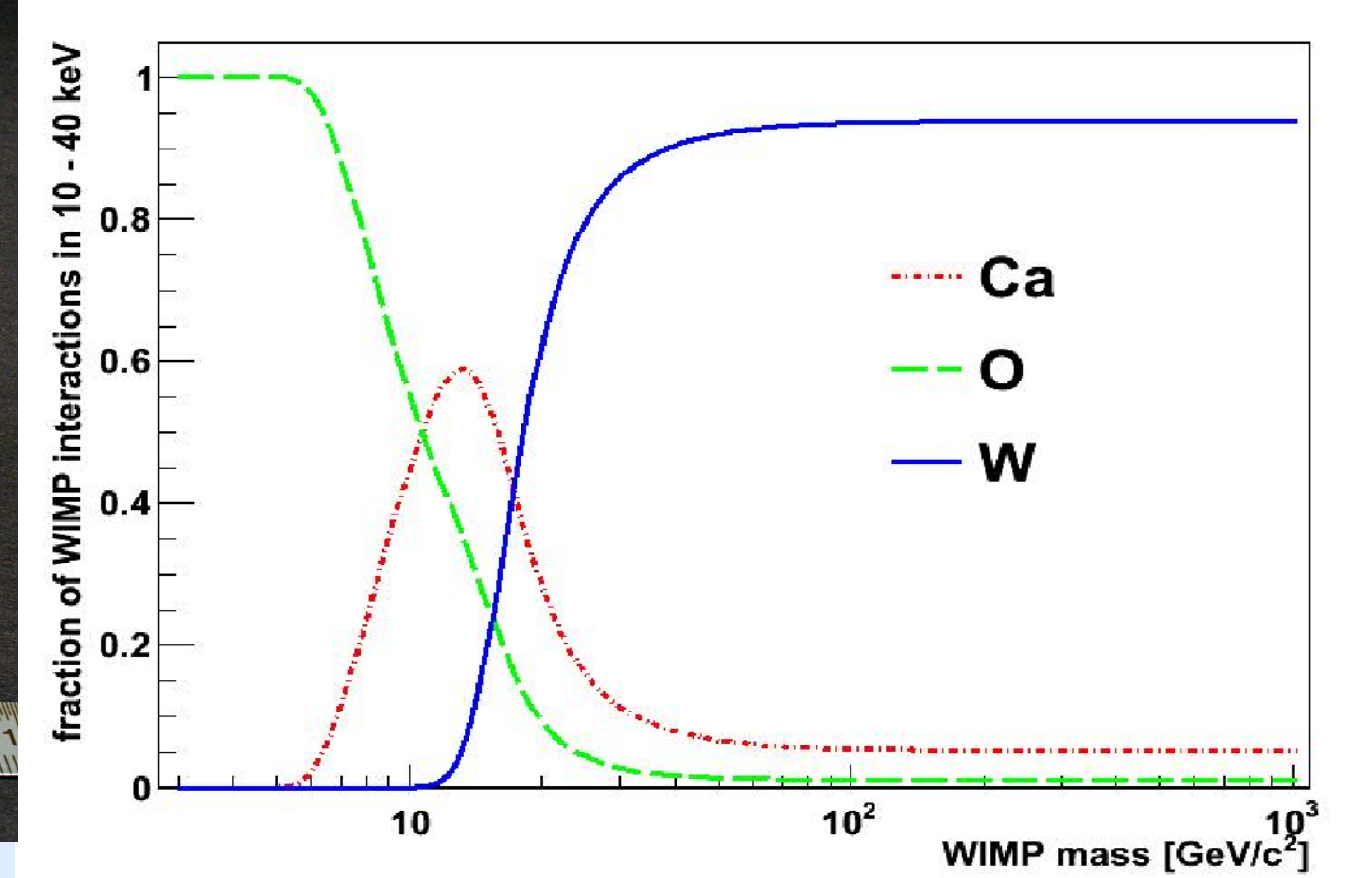


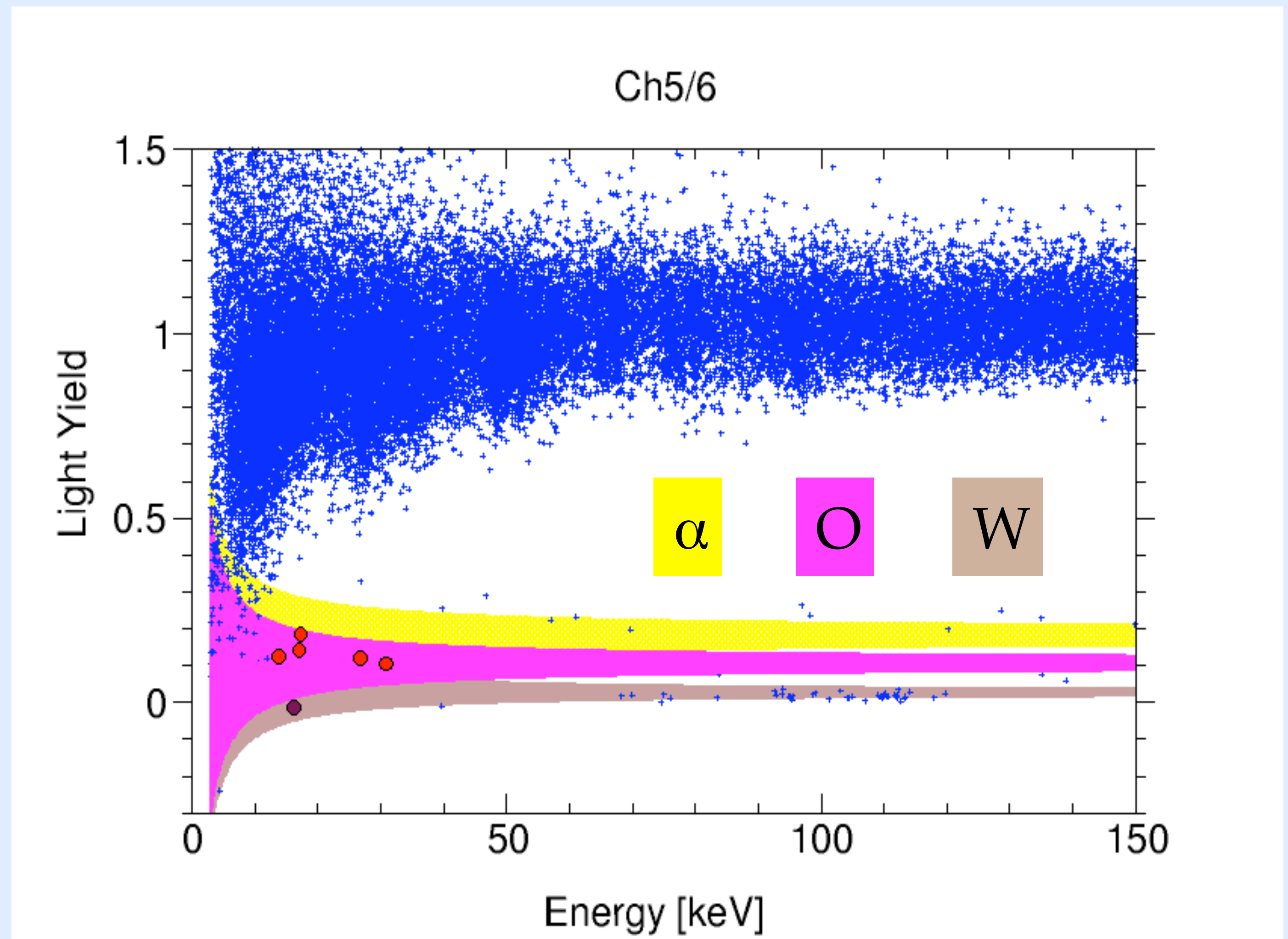
[courtesy: Juan Collar]



[arXiv:1002.4703]





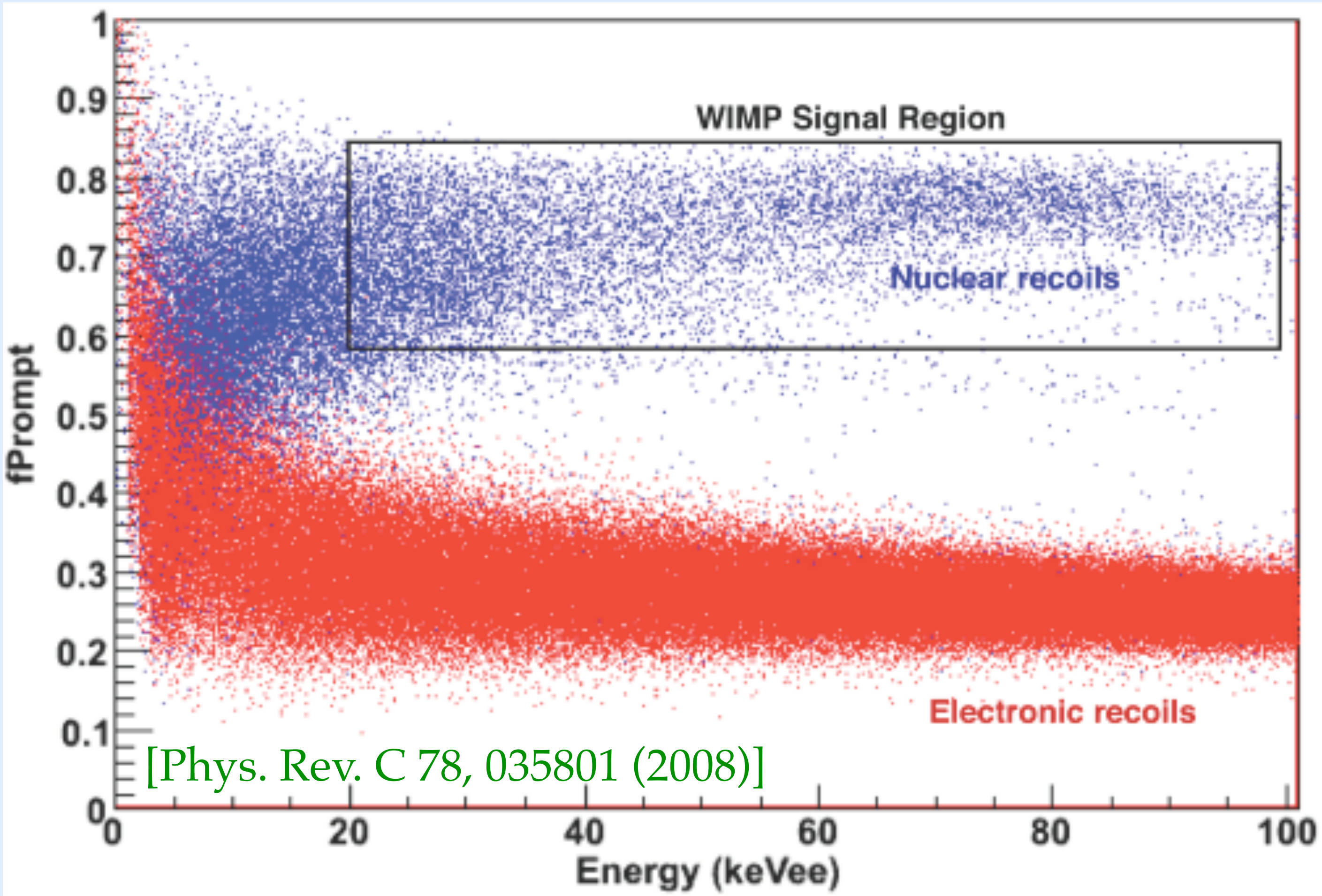


- $CaWO_4$ scintillating bolometers at Gran Sasso
- 10 keV threshold
- ~400 kg d (~ 10 kg of detectors)
- 32 events (~9 expected)
- neutrons, α leakage?
- low mass WIMPs?

[from: Wolfgang Seidel @ IDM 2010]

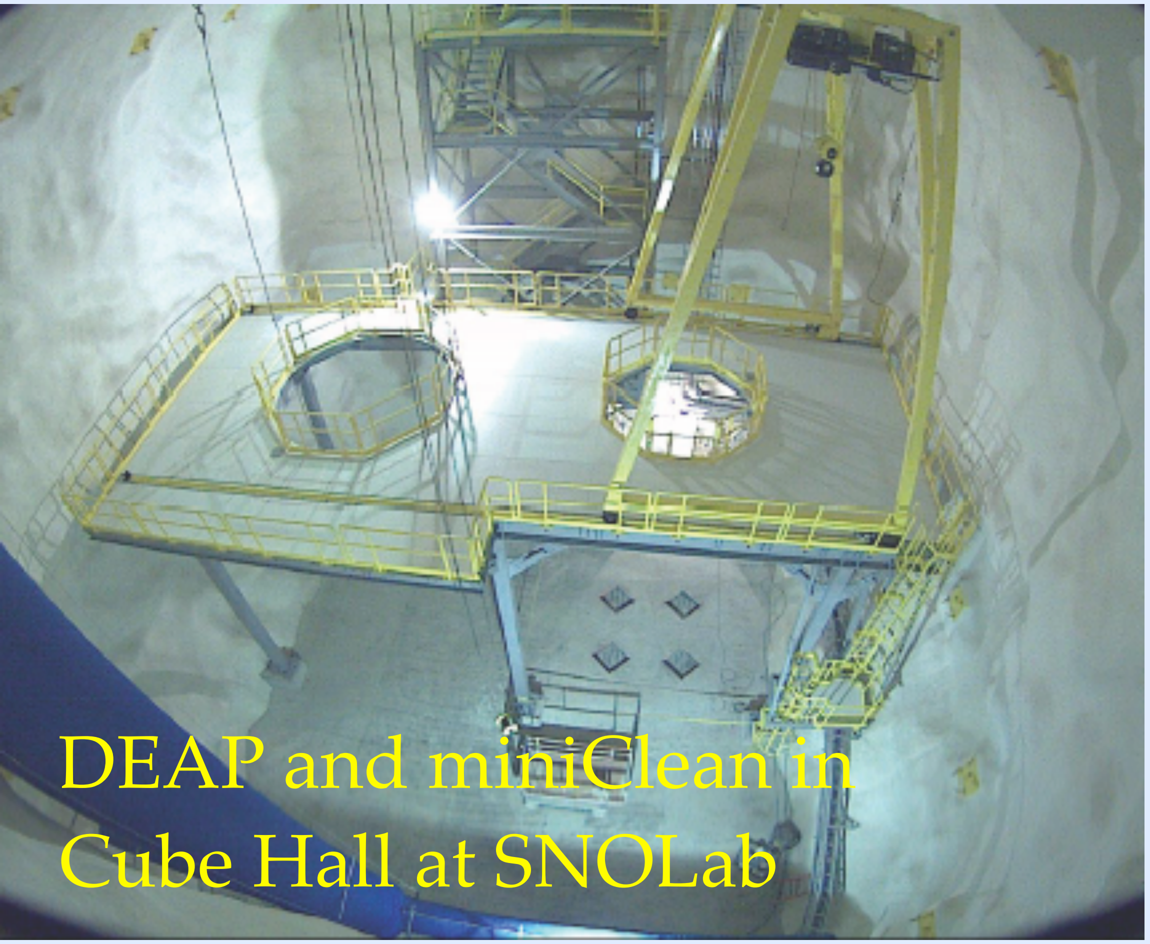
Argon: DEAP/CLEAN

- argon and neon allow to perform pulse shape discrimination of primary scintillation, S1 (fraction of light in first ~100 ns of the pulse)
- based on the very large difference in decay times between singlet (≈ 7 ns) and triplet (1.6 μs) components of the emitted UV light



[Phys. Rev. C 78, 035801 (2008)]

- 1.6×10^{-6} discrimination for 64-128 keVr

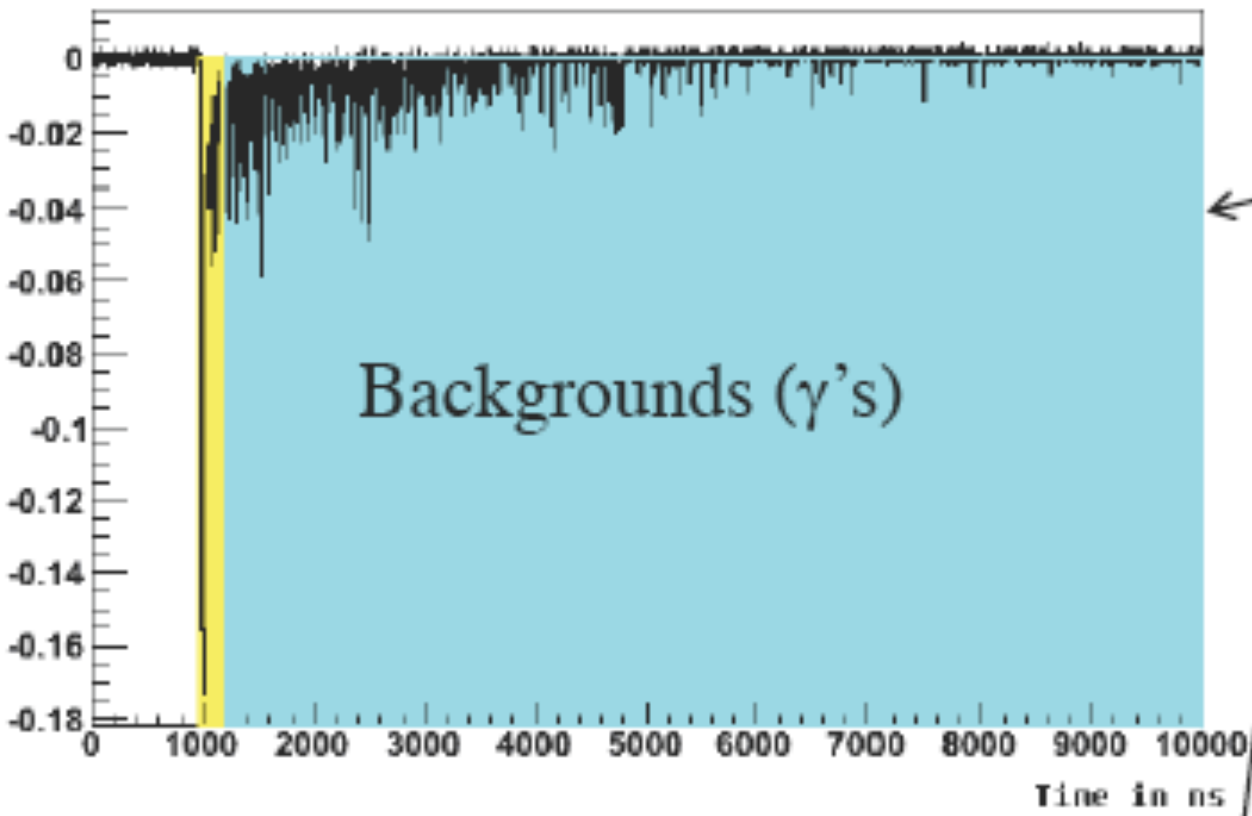


- theoretical discrimination power could exceed 10^8! [Boulay, Hime (2004)]
- DEAP-I (7 kg LAr) has one event in 9.3×10^9

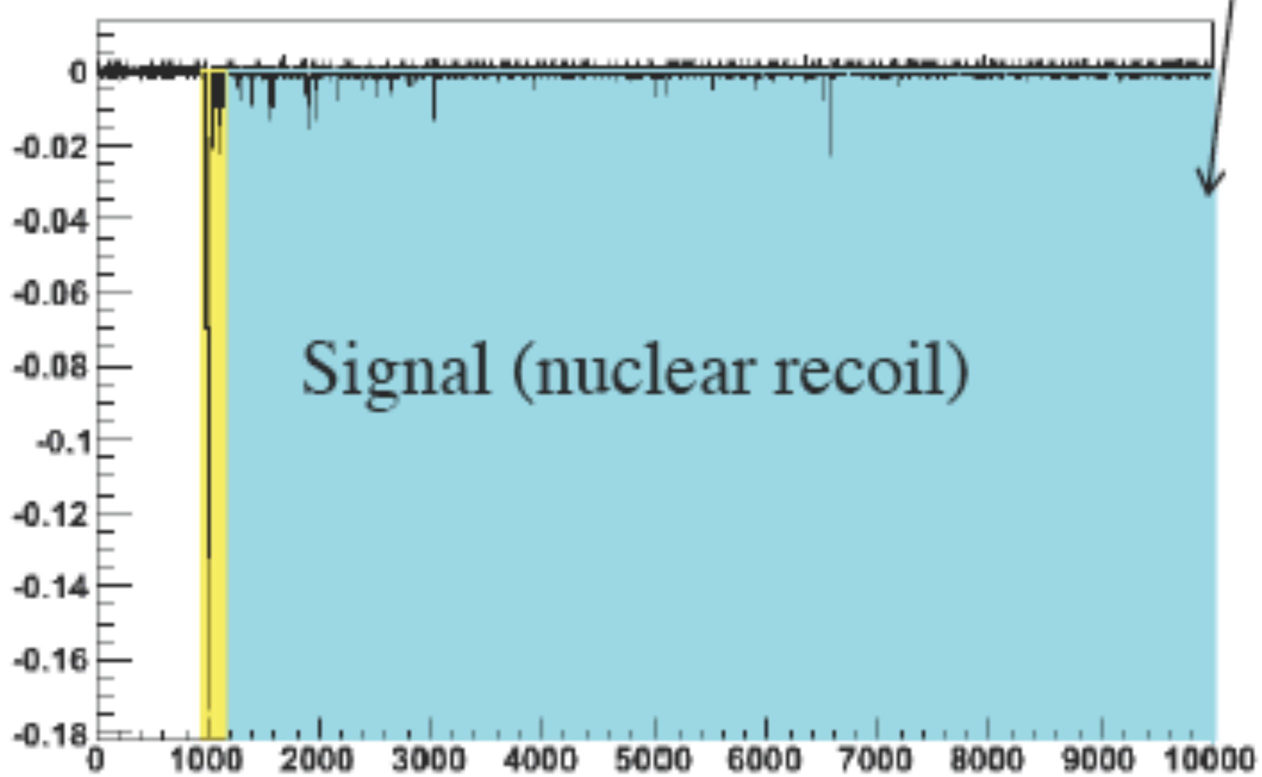
- miniClean: 500 kg LAr (150 kg LNe)
- DEAP: 3600 kg LAr
- both detectors are single phase

[courtesy: Dan McKinsey]

Argon: pulse shape discrimination



PMT signals



DEAP 3600 @ SNOLAB

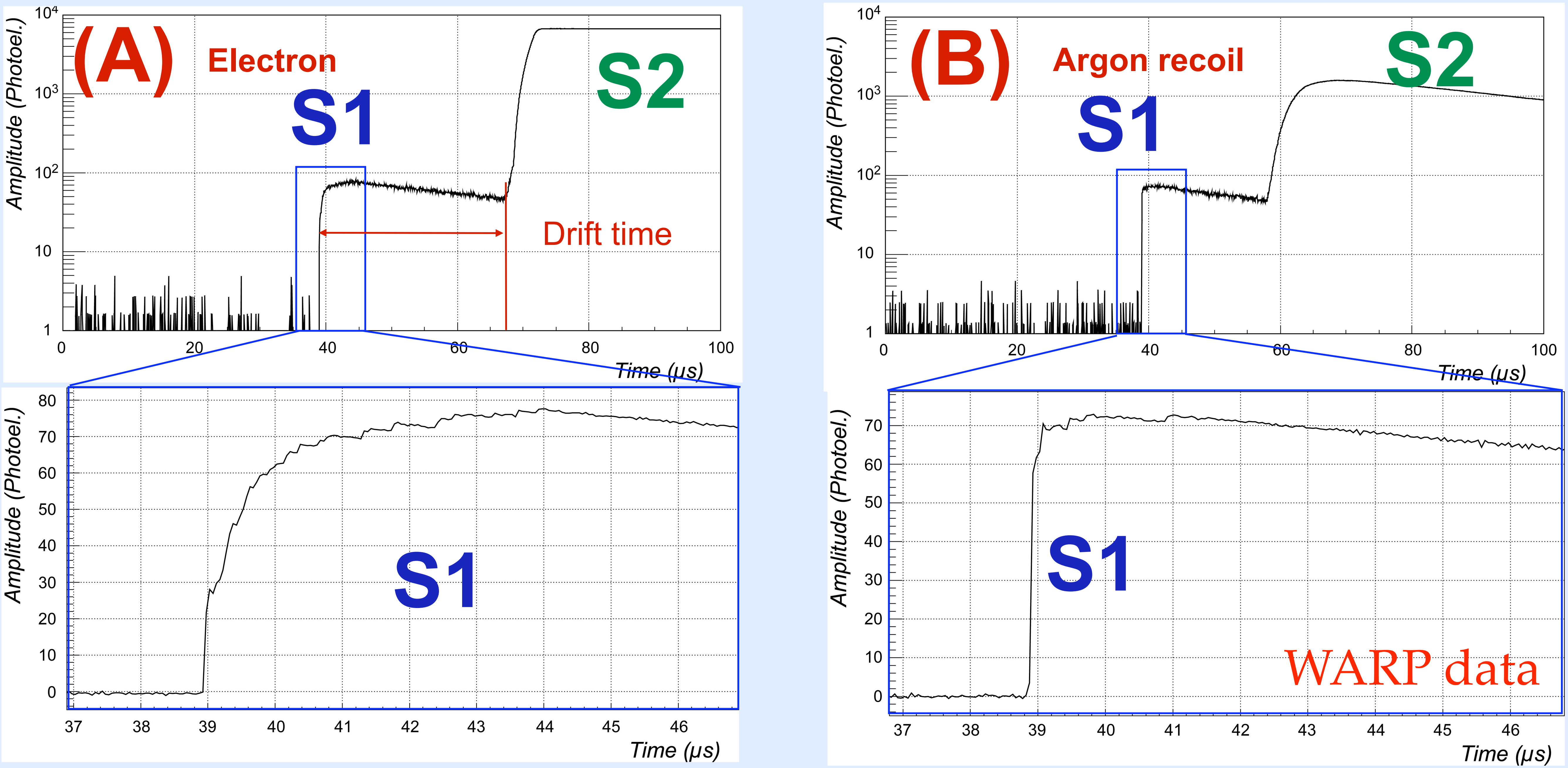
$$F_{prompt} = \frac{\text{PromptPE }(150ns)}{\text{TotalPE }(9\mu s)}$$

Yellow:	Prompt light region
Blue:	Late light region

triplet/singlet ratio:
Minimum ionizing: ~ 3/1
Nuclear recoils: ~ 1/3

[courtesy: Mark Boulay]

discrimination in 2-phase Ar



1. S2/S1 (ionization/primary scintillation)
2. rise time of the S1 pulse (fast for recoils, slower for mip's)

[courtesy: Cristiano Galbiati]

the DARKSIDE *design*

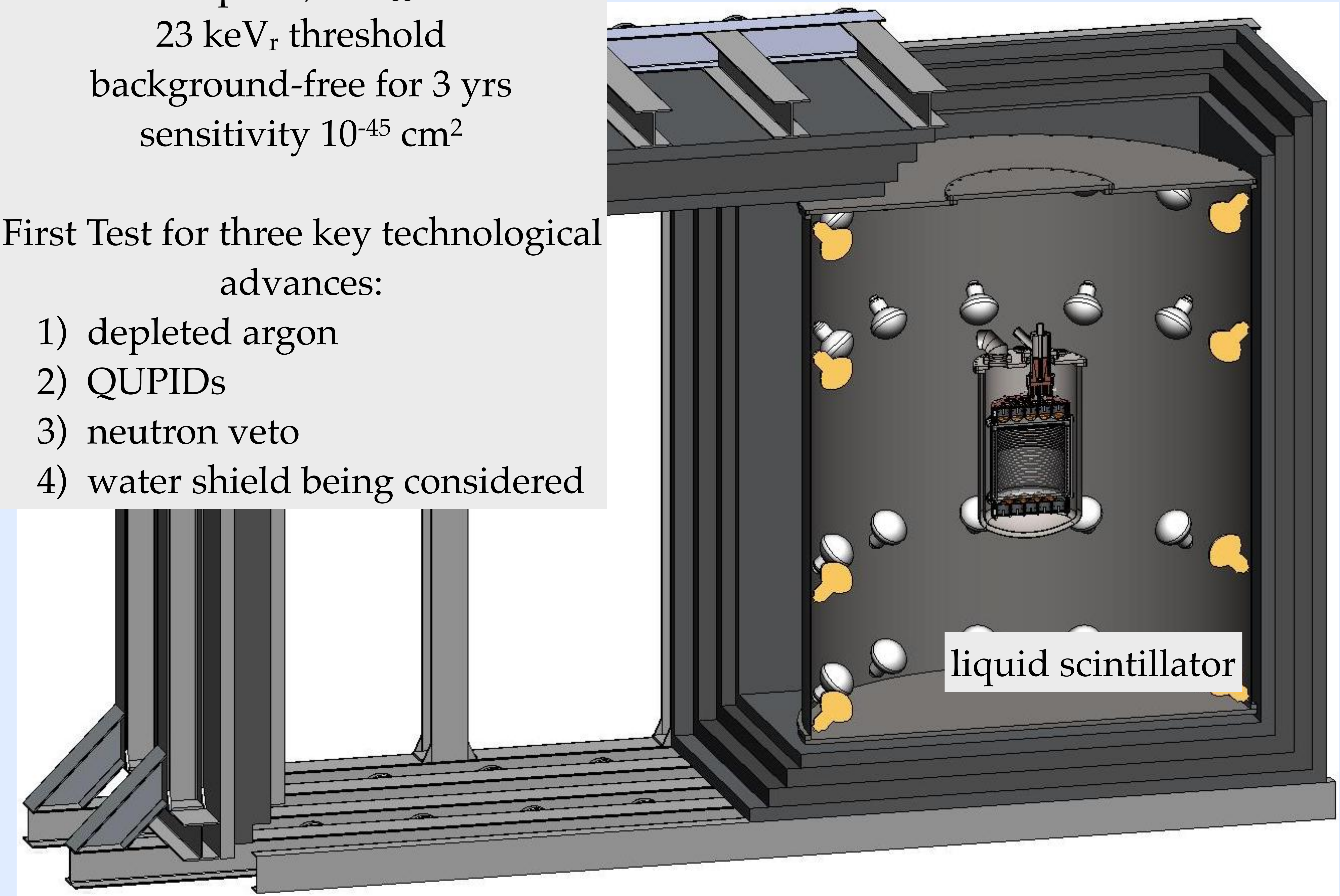
- argon TPC with readout of both primary scintillation light and ionization, for accurate 3D position reconstruction
- argon scintillation is produced in very much the same way as in Xe
- 2-phase design allows for the collection of electronic signal (with gain)
- double discrimination: S1/S2 ratio and pulse shape analysis of S1
- low ^{39}Ar (i.e. depleted in this radioactive isotope) argon from underground in view of a very large (several tons) detector
- ultra-low background detector design
- high efficiency, compact neutron shield (borated liquid scintillator)

DarkSide-50

50 kg active mass
5 ph.el/keV$_{ee}$
23 keV$_r$ threshold
background-free for 3 yrs
sensitivity 10^{-45} cm^2

First Test for three key technological advances:

1) depleted argon
2) QUPIDs
3) neutron veto
4) water shield being considered



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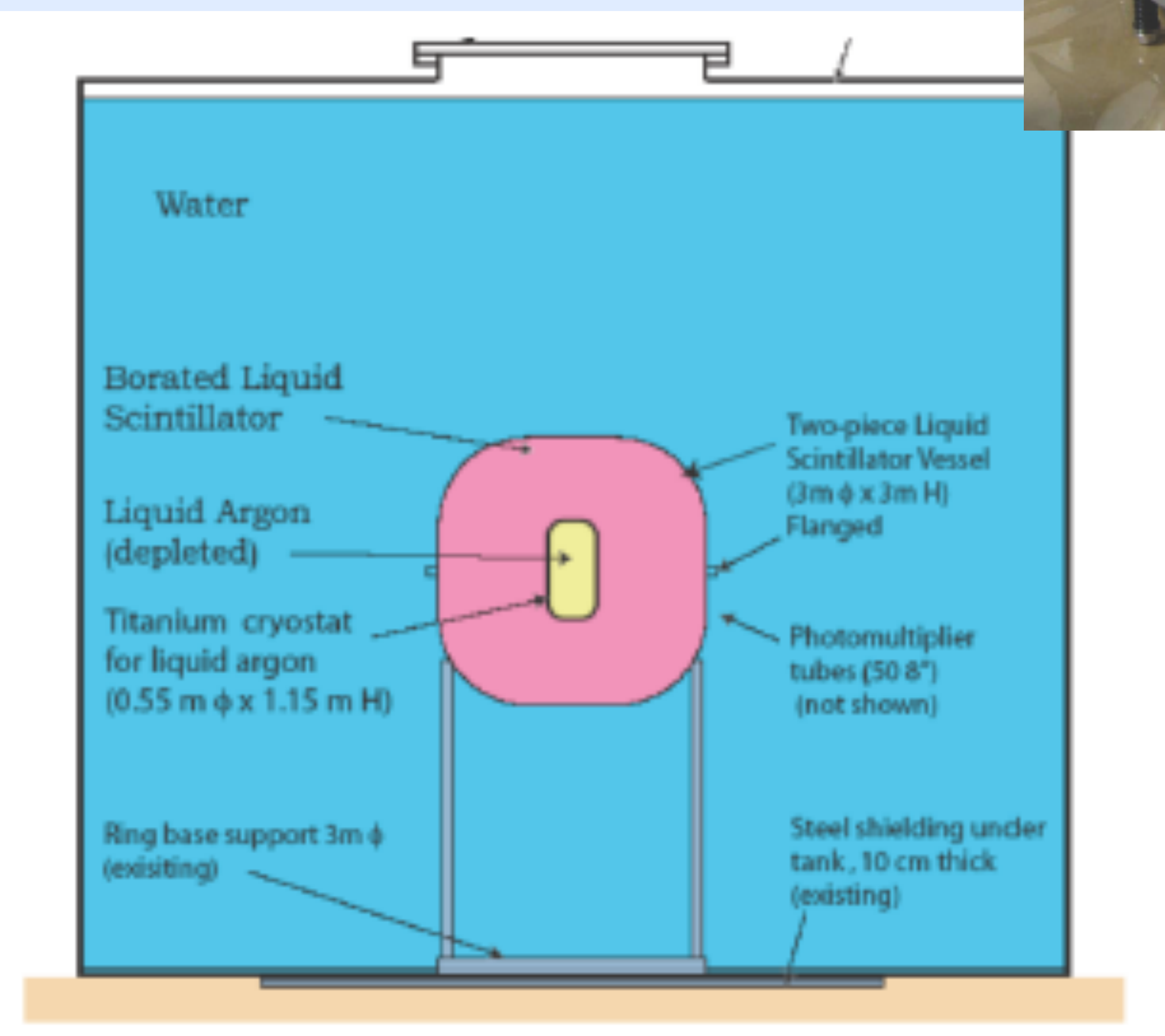
DarkSide-50

← 10 kg prototype in Princeton

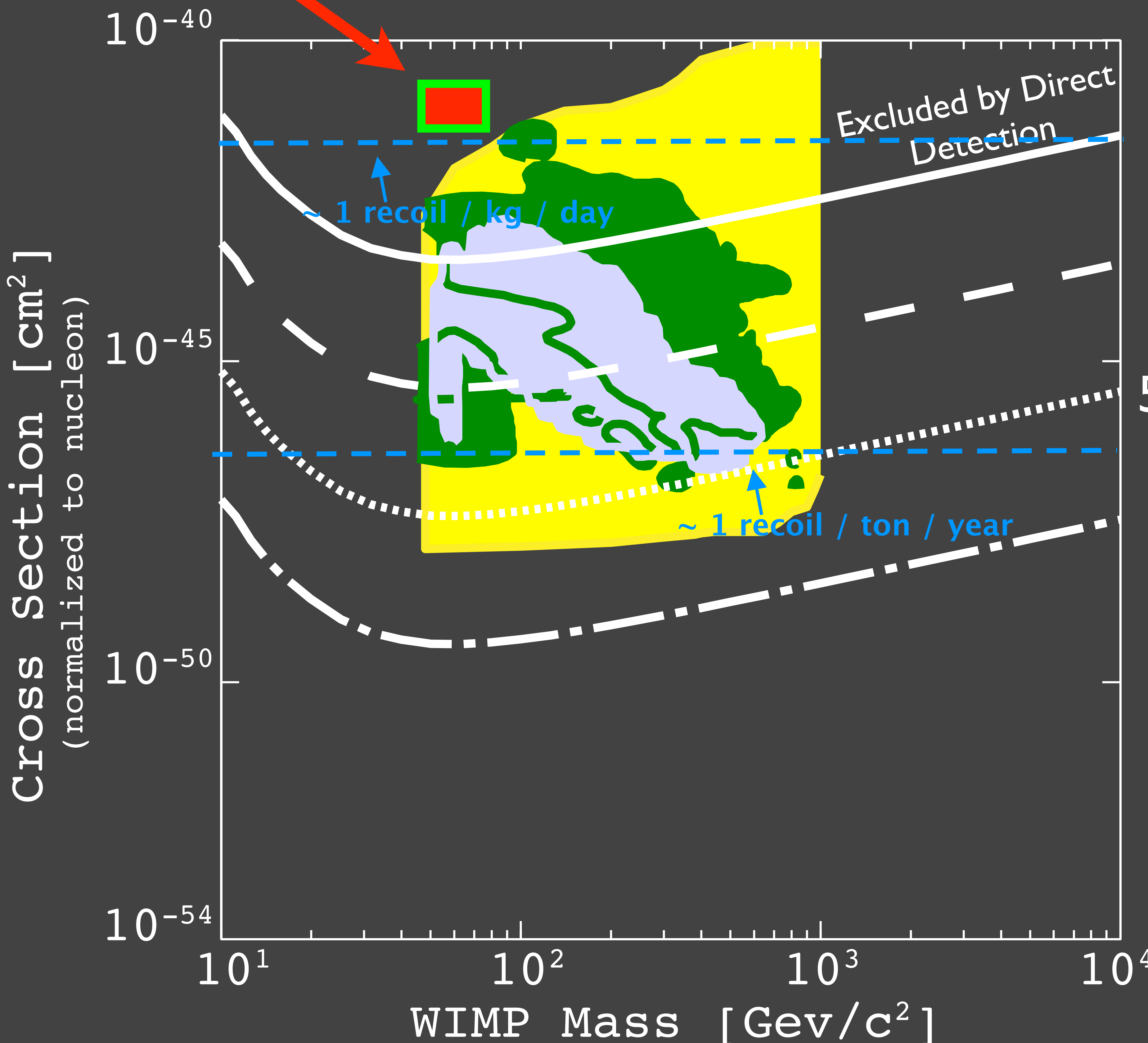
Ar distillation column at Fermilab (PAB) ↓

in the CTF @ Gran Sasso



SUSY Exploration

DAMA claim



Current Limit (~10 kg)

100 kg Ge/Xe -400 kg Ar

5 t Ge/Xe - 20 t Ar

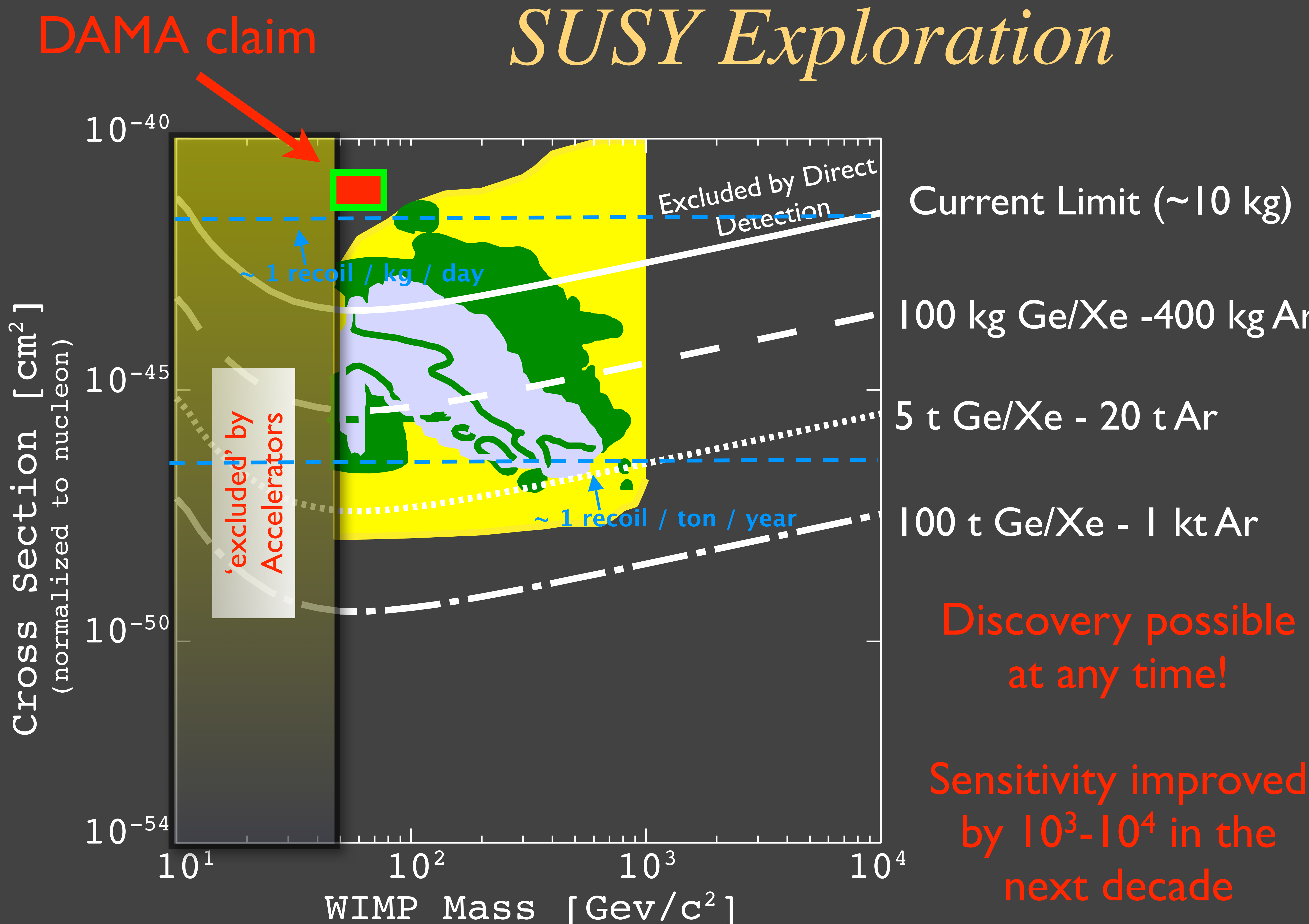
100 t Ge/Xe - 1 kt Ar

Discovery possible at any time!

Sensitivity improved by 10^3-10^4 in the next decade

R. Schnee

SUSY Exploration



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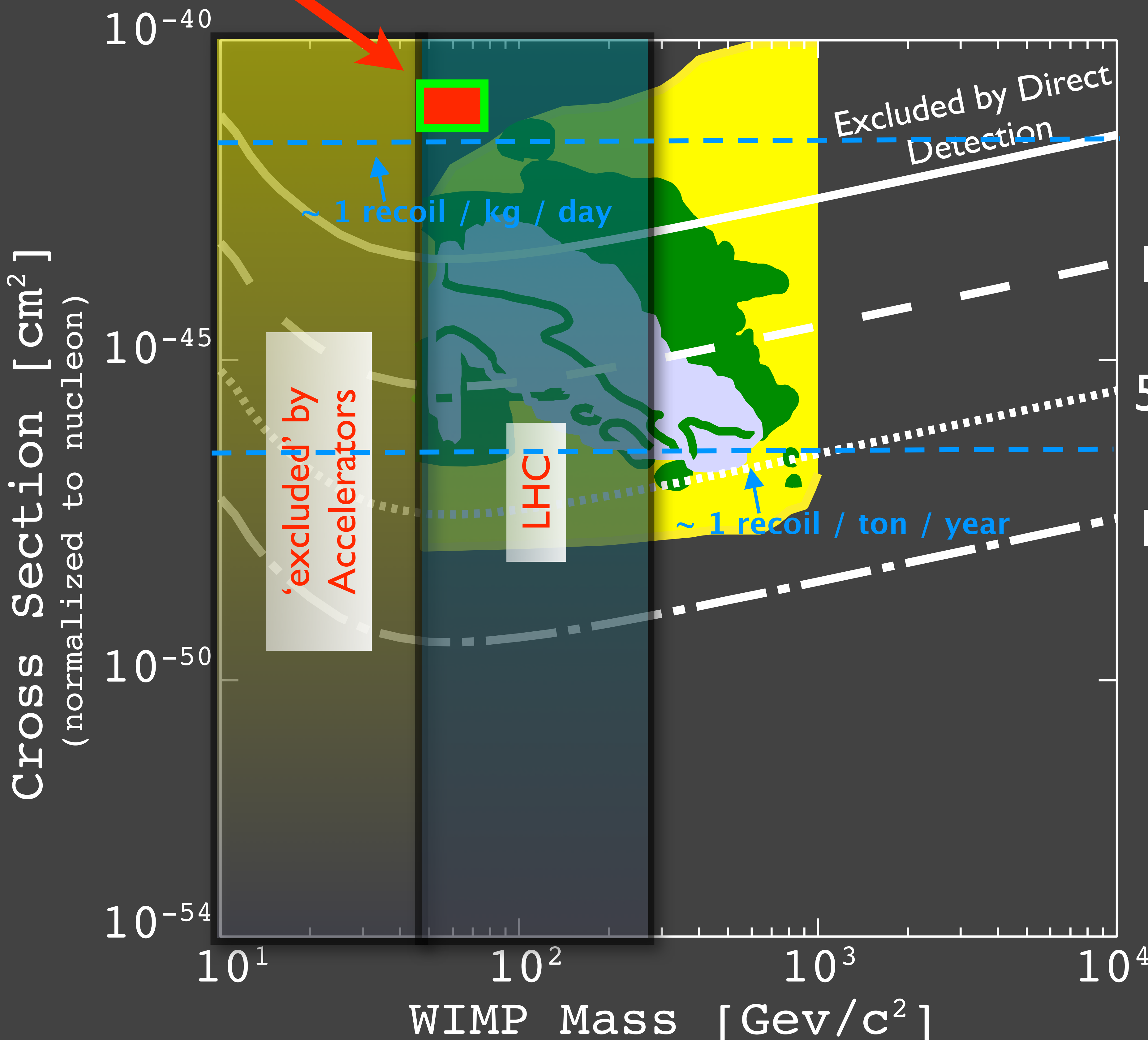

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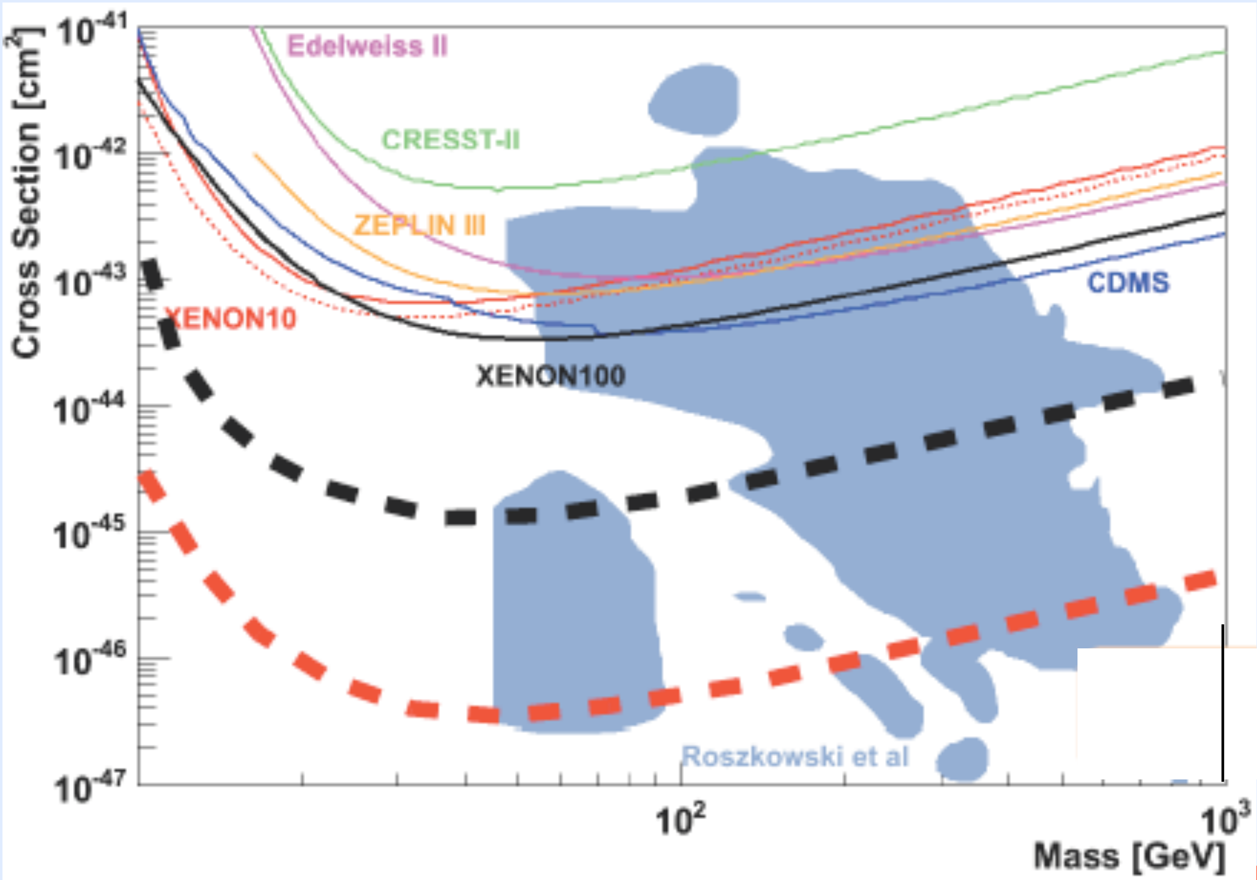
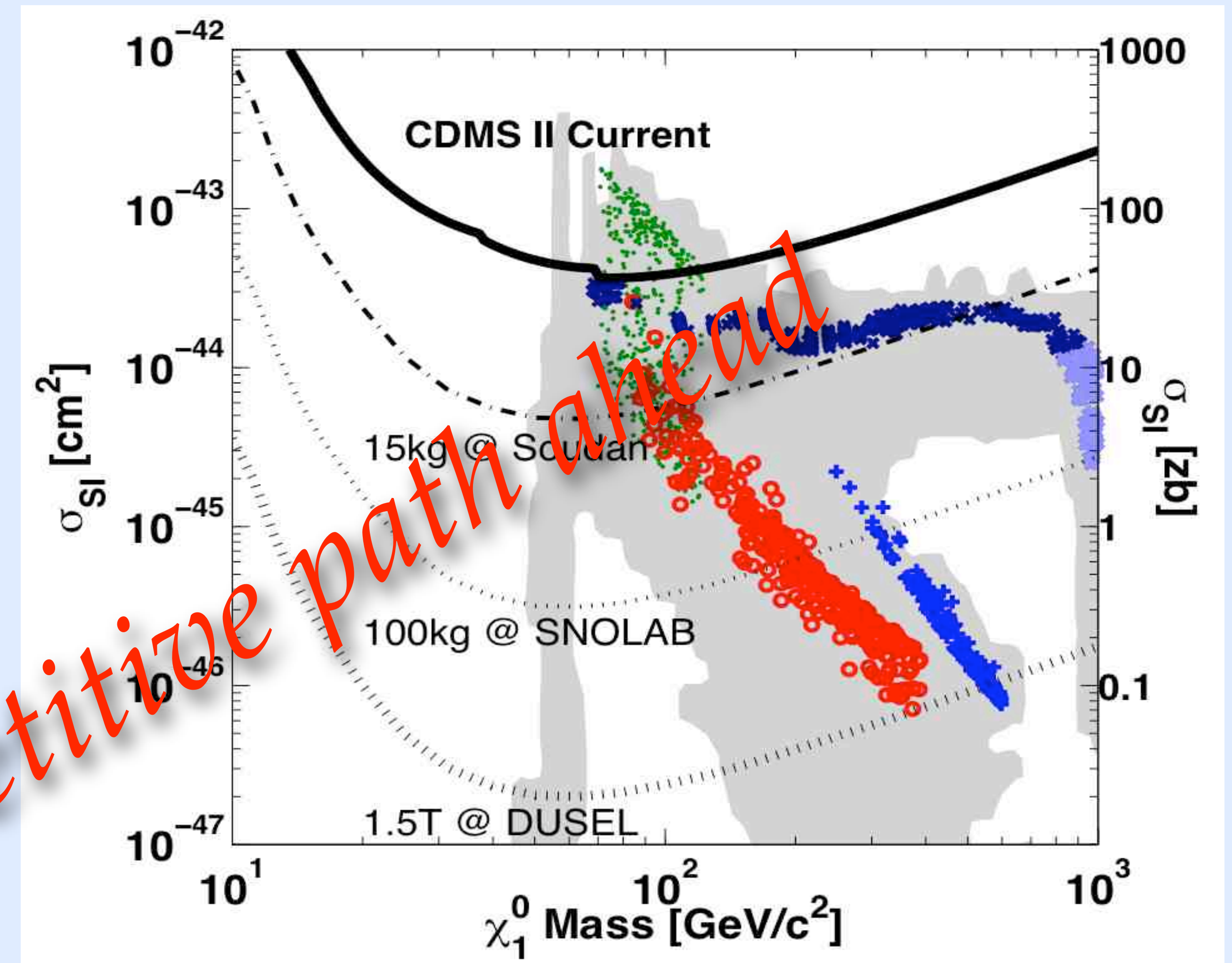
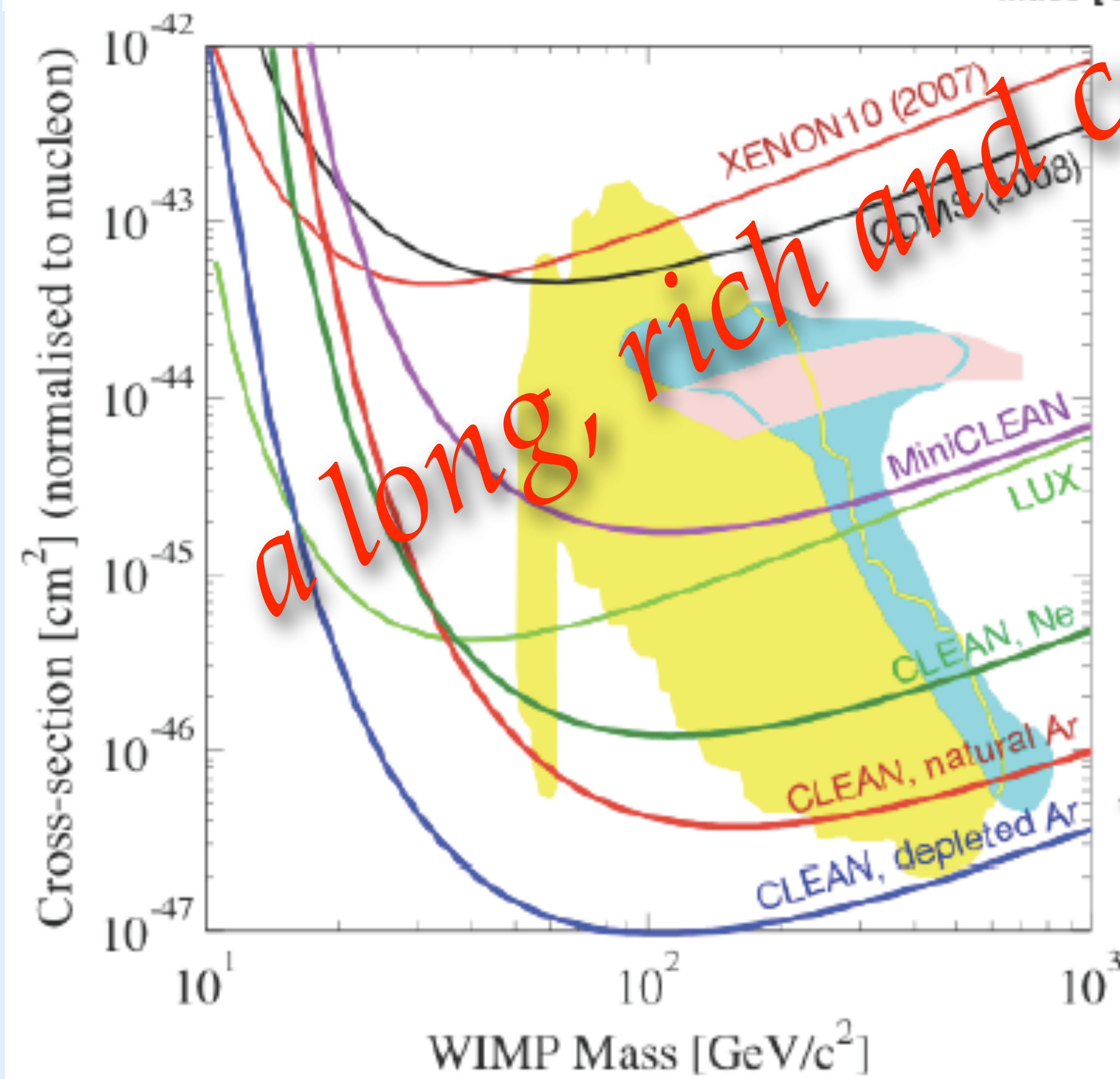
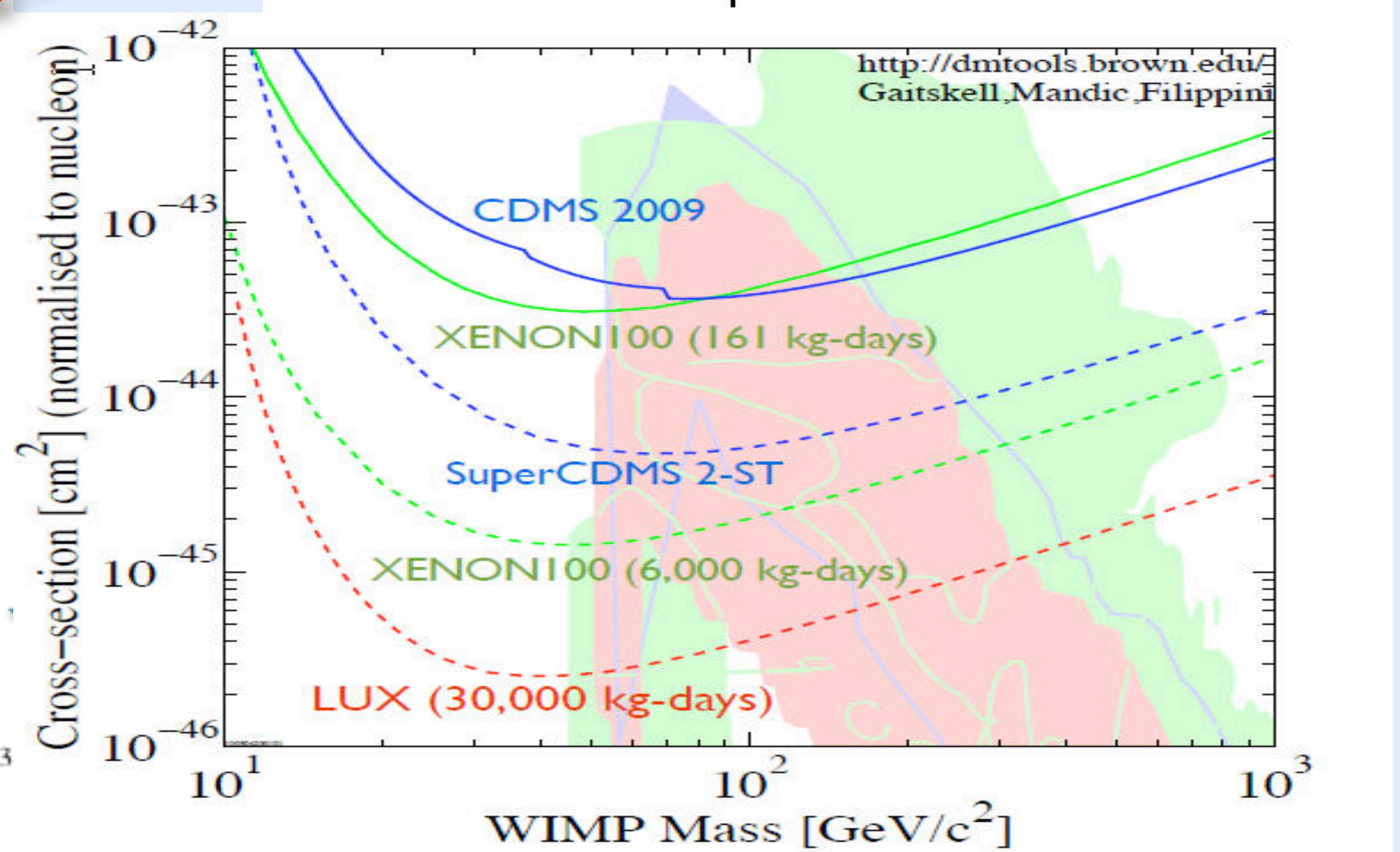








a long, rich and competitive path ahead

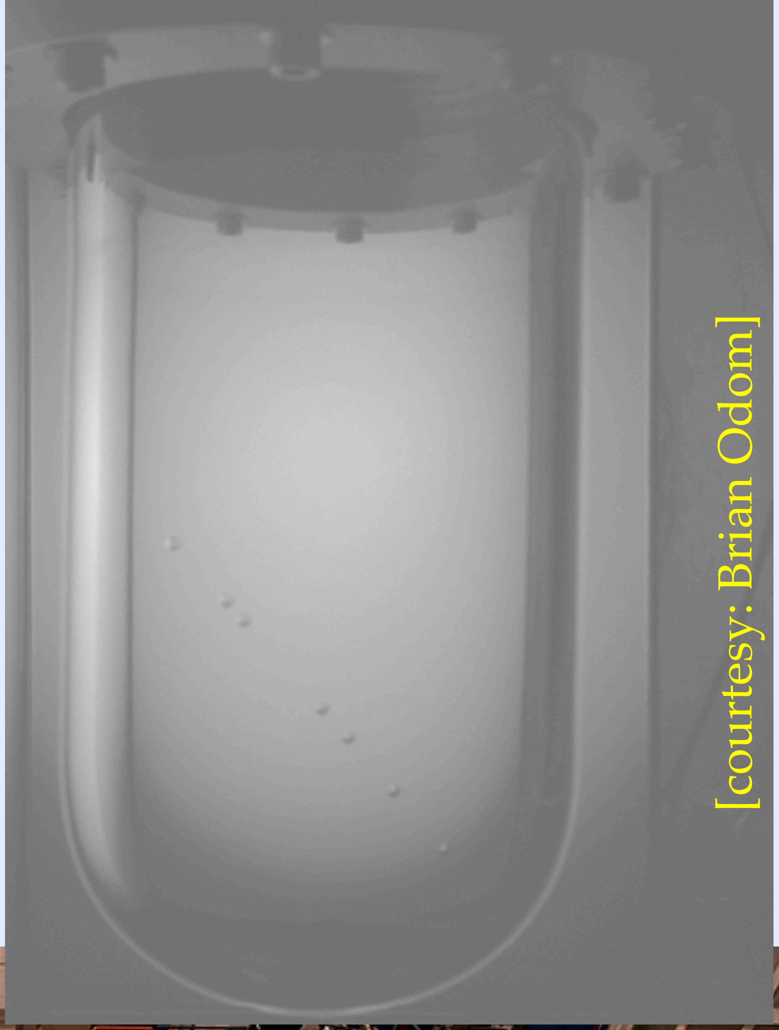
more food for thought

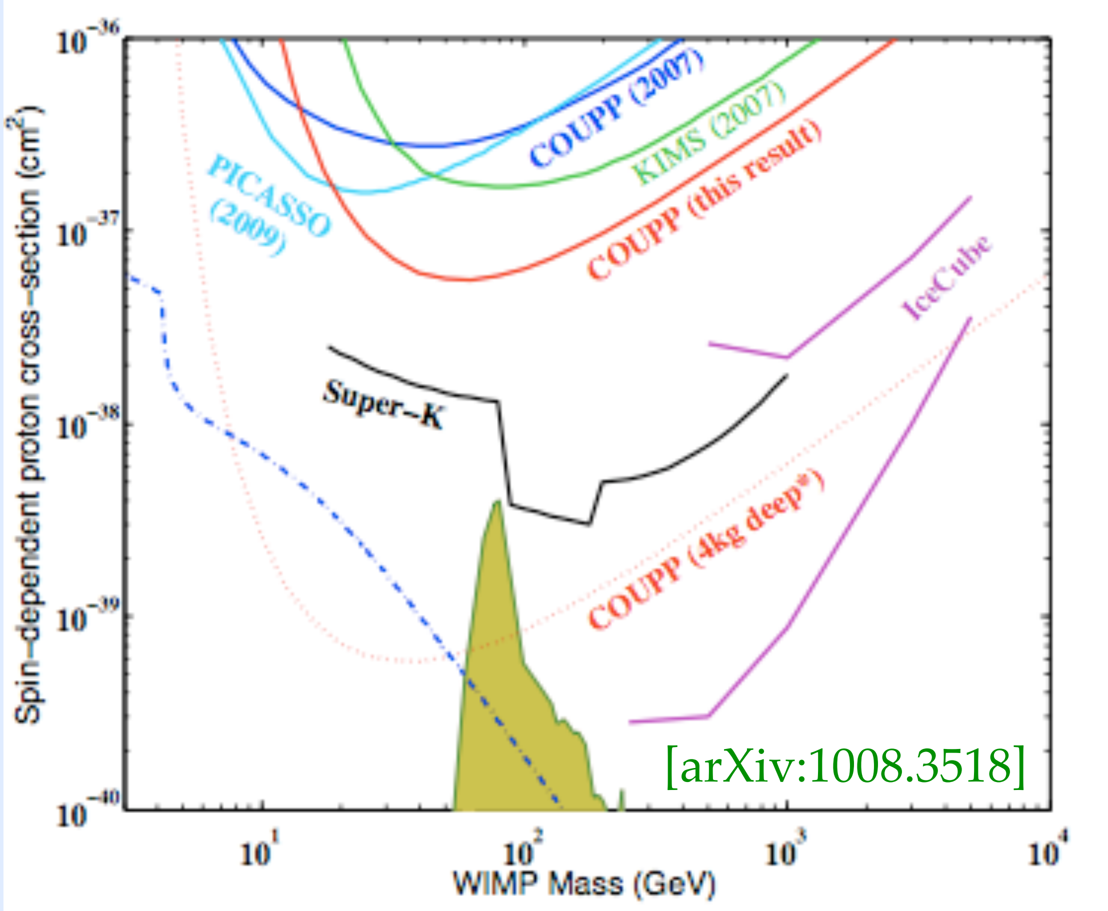
- spin-dependent dark matter to matter coupling
- inelastic dark matter (a spectrum of WIMPs) [**Smith, Weiner,** Phys. Rev. D 64, 043502 (2001)]
- axions as candidate dark matter

- continuously think hard about possible backgrounds and ways they can manifest themselves; we are defining the sensitivity of our experiments based on a complete understanding of backgrounds at energies which might not have been explored yet
- be your first critic (see *e.g.* Ralston, arXiv:1006.5255)

COUPP

- superheated liquid CF_3I (3.5 kg) ran as a bubble chamber @ Fermilab (threshold detector)
- spin-dependent searches (large masses possible)
- ionizing energy releases nucleate bubble
- fantastic discrimination against β/γ events (just run in a mode where they do not nucleate); main challenge: α background (acoustic discrimination!)





outlook

- direct dark matter searches are proceeding at a very sustained pace and are starting to probe some SUSY parameter space

- LHC is now in operation and will most likely make a 'quantum leap' in exploring the existence of possible dark matter particles

- the two approaches are *a priori* both in competition and complementary to each other; they will continue to advance together with indirect searches of dark matter annihilation products, while cosmological observations will give ever more precise indications of dark matter properties

- increasing sensitivity of experiments in seemingly known territory might always yield pleasant surprises, until dark matter is finally understood

trivia

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(I could not be present to retrieve the prize in person, and they would not send it to me by mail!)

maybe a good sign for a bigger prize to come?

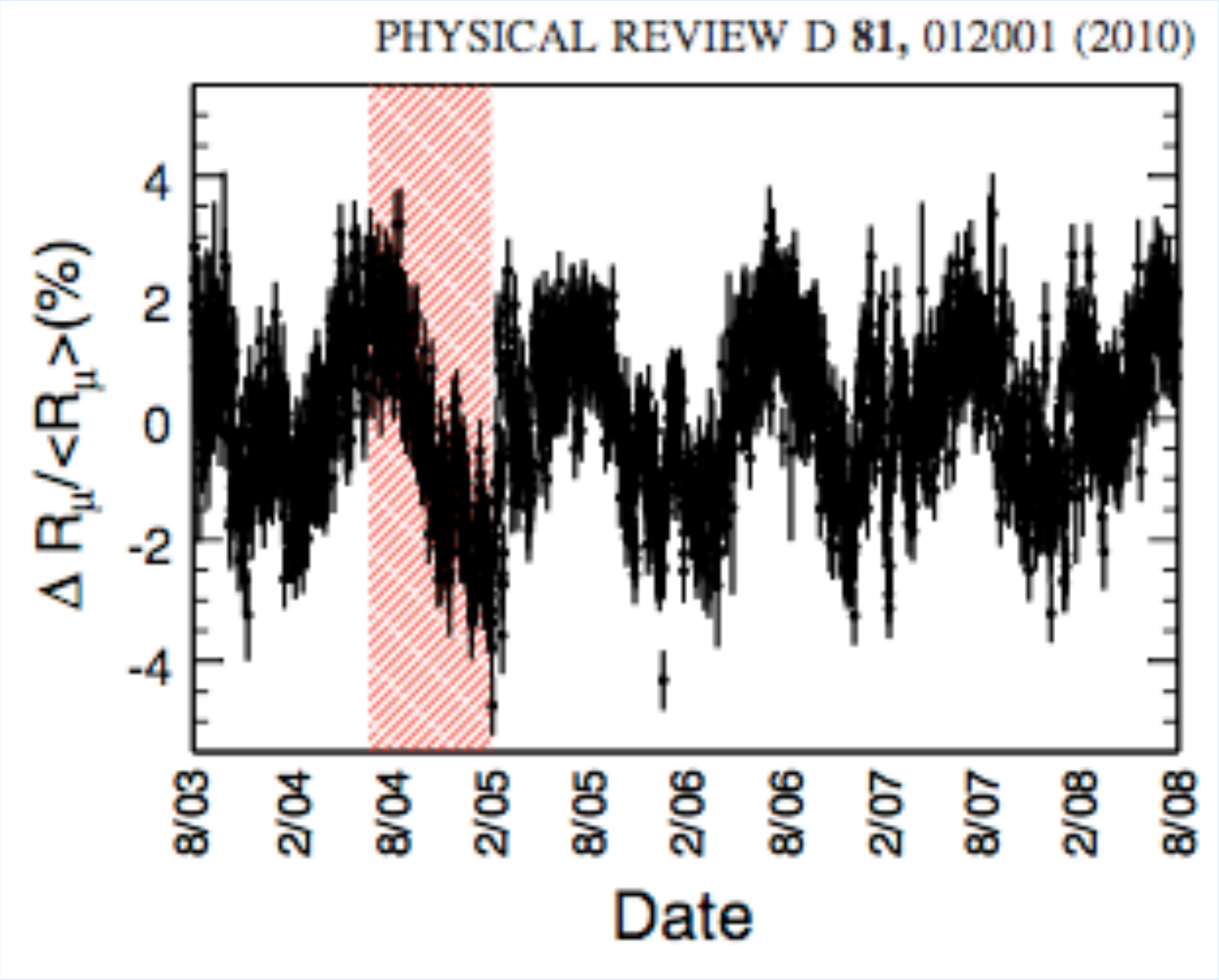
a subtle suggestion was sent my way one sunny day in a Berkeley subway station .....


LET YOUR DARKSIDE OUT
Wii
11.17.09
CAPCOM
RESIDENT EVIL


LET YOUR DARKSIDE OUT
LET YOUR DARKSIDE OUT
Wii
11.17.09
CAPCOM
RESIDENT EVIL
THE DARKSIDE CHRONICLES

thank you, and best wishes for a *massively* dark future!

further interesting topics



- seasonal variations of the muon flux measured by MINOS

- do we really understand neutron backgrounds thoroughly?