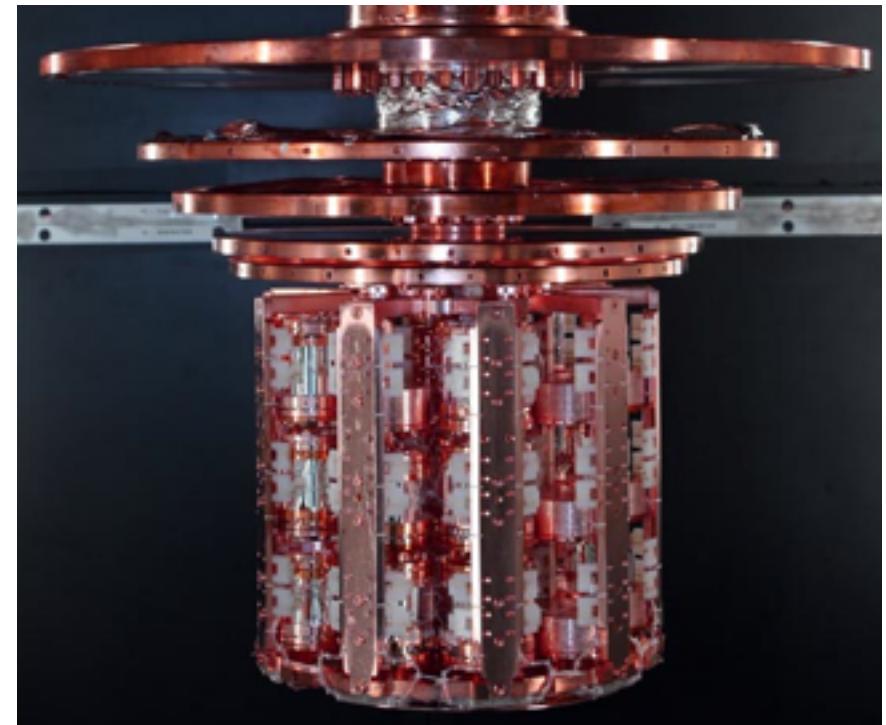


Direct Detection with Cryogenic Experiments



Enectali Figueroa-Feliciano

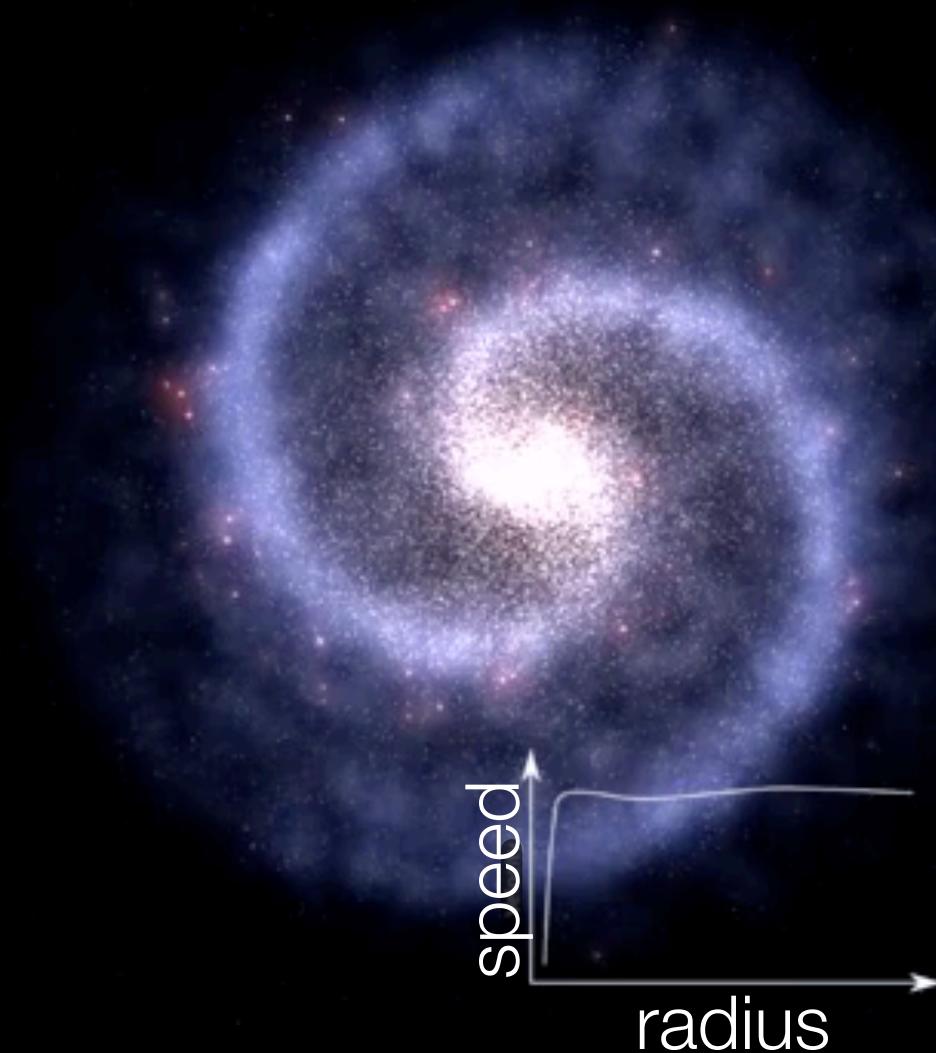
Outline

- The Dark Matter Problem
- Direct Detection Principles
- Cryogenic Detectors
 - CRESST
 - EDELWEISS
 - EURECA
 - SuperCDMS

The Dark Matter Problem

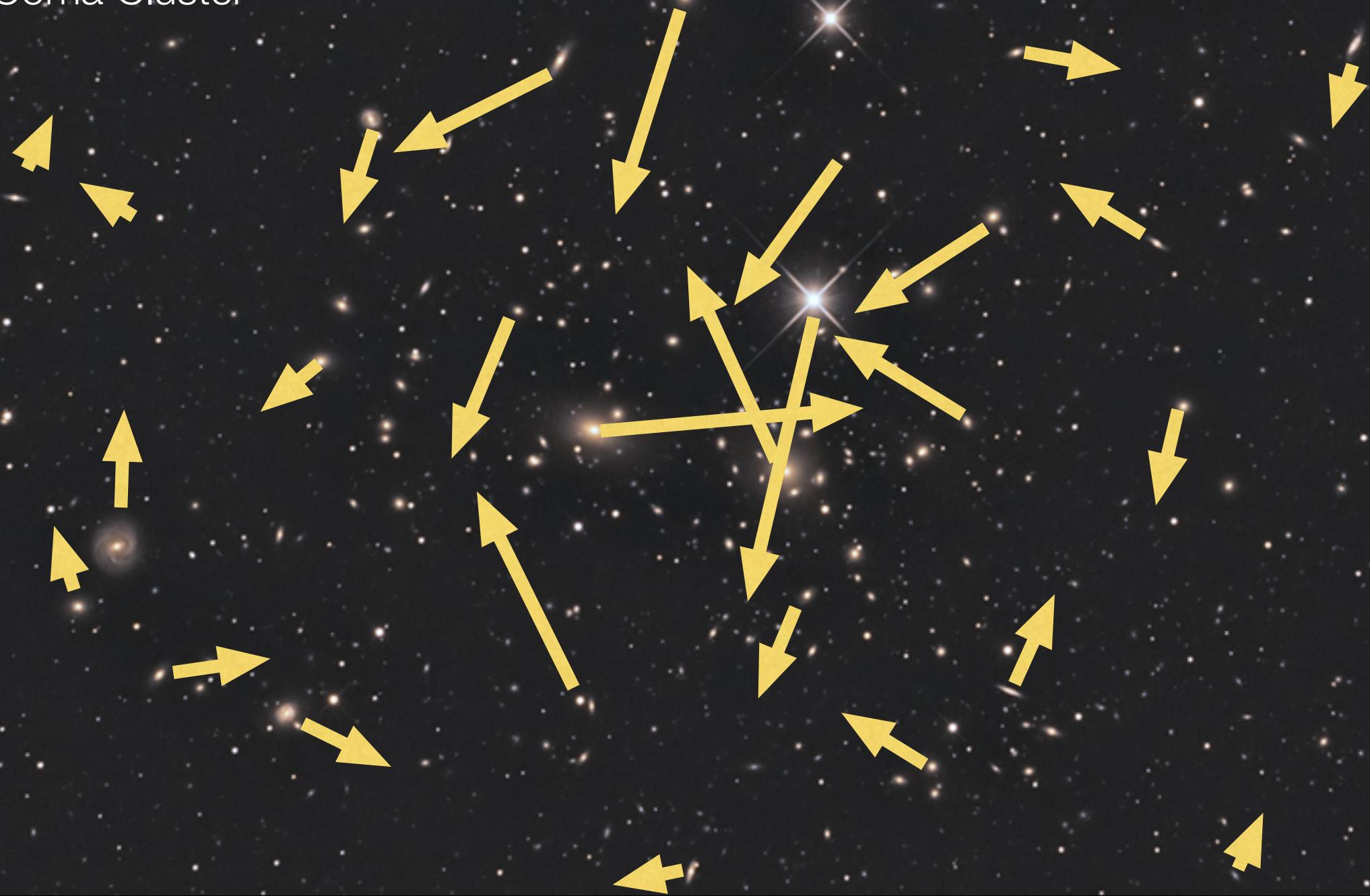
Galaxy Rotation Curves

orbits at high radius are
faster than expected

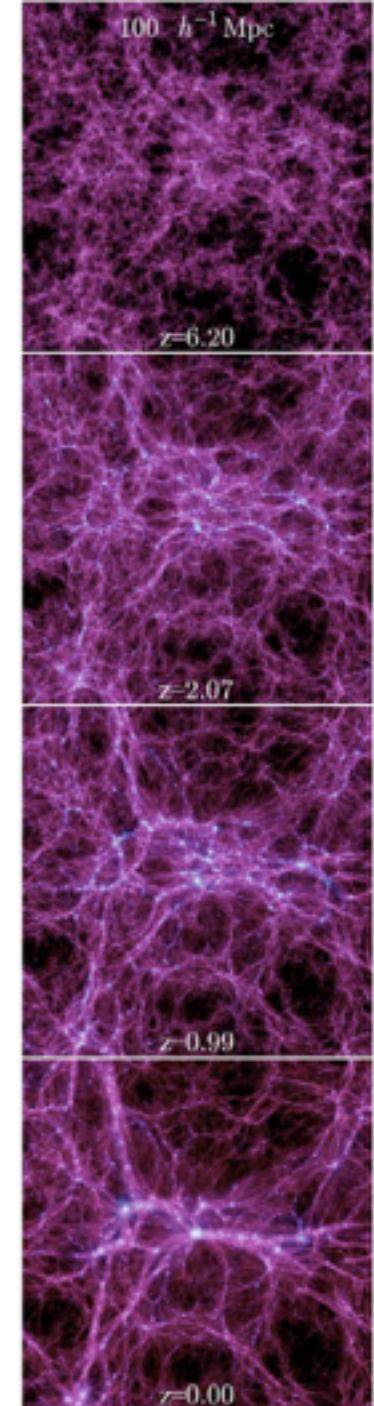
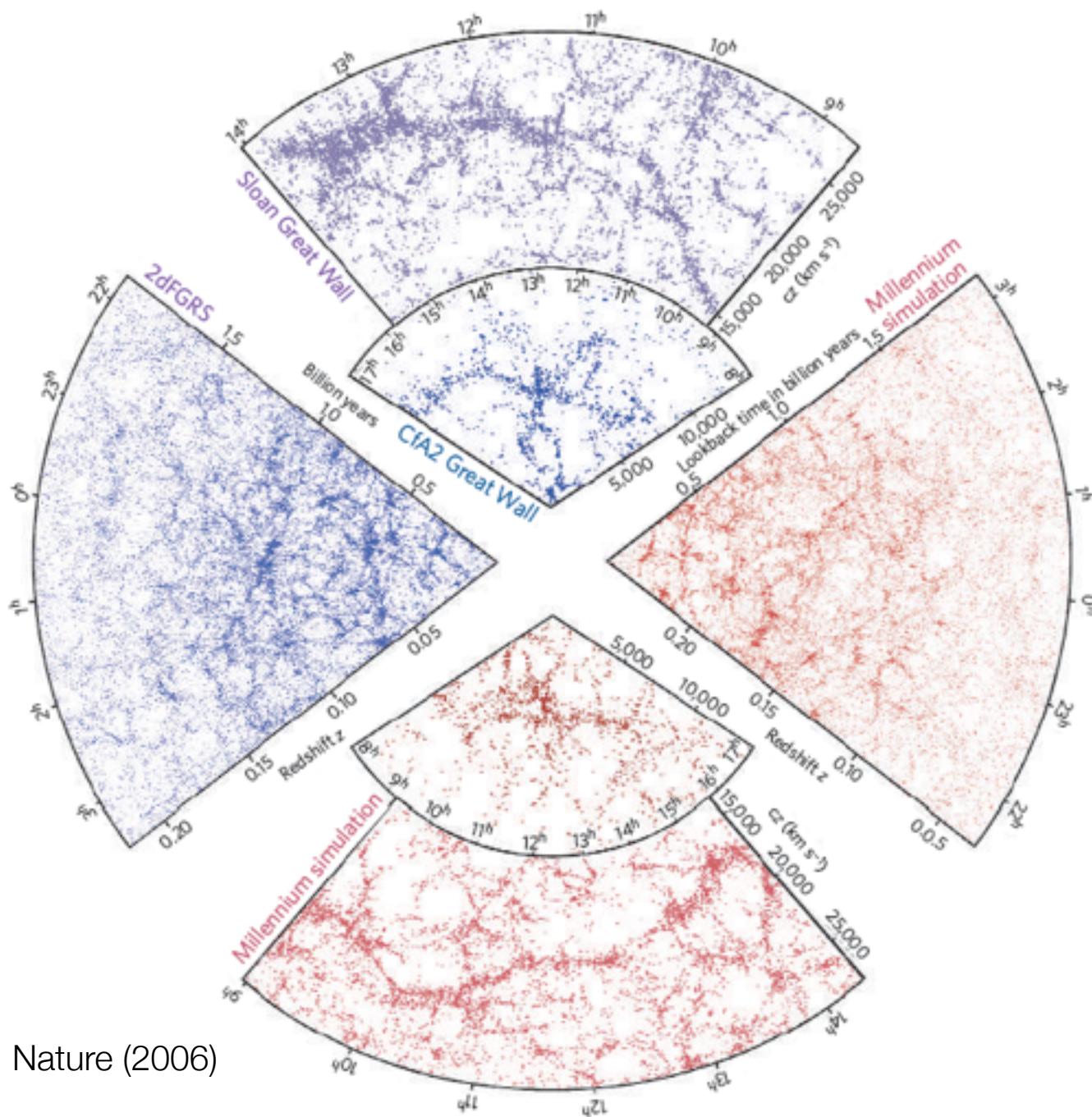


Galaxy Velocities in Clusters

Coma Cluster

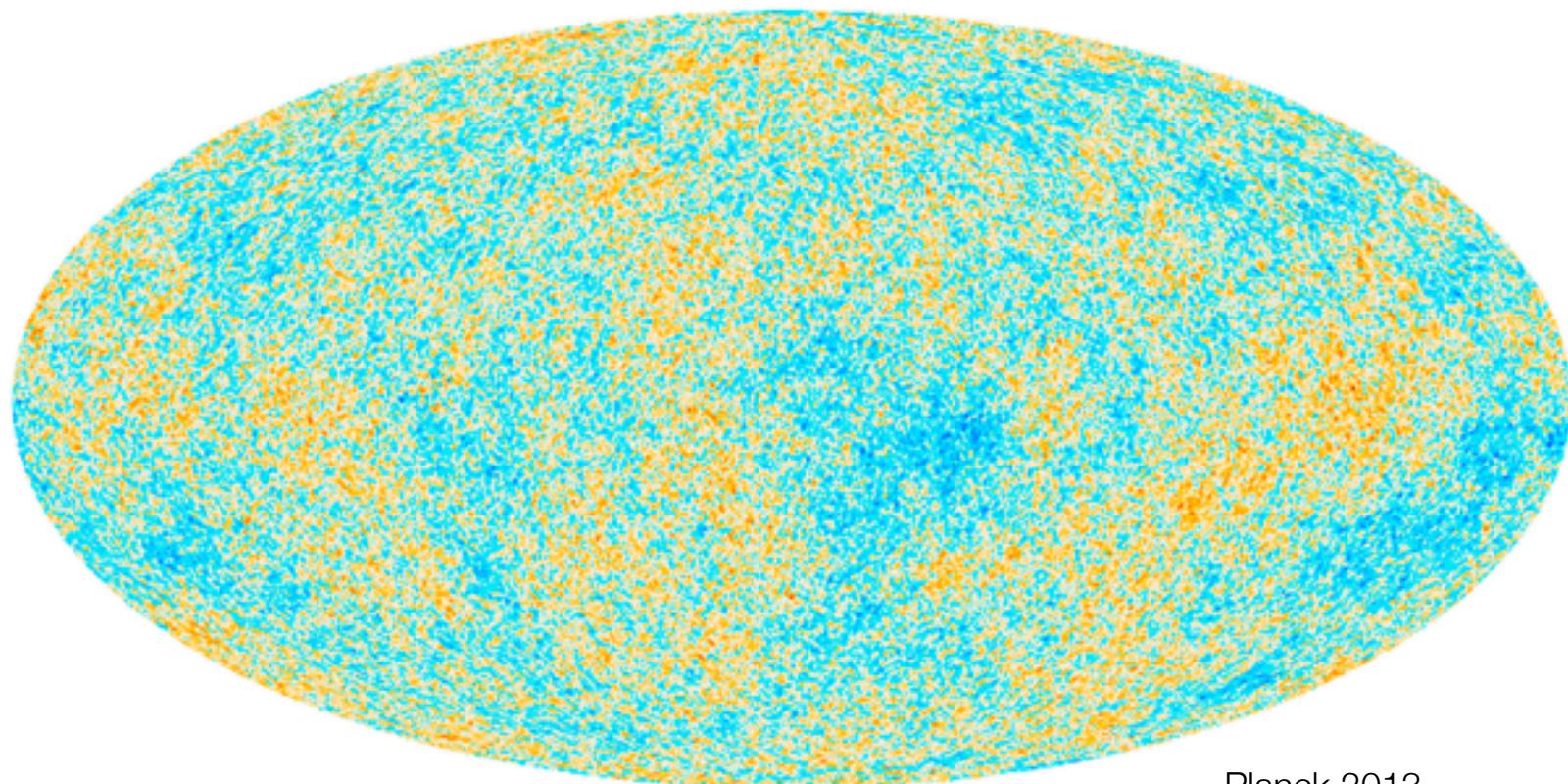


Models of Structure Formation



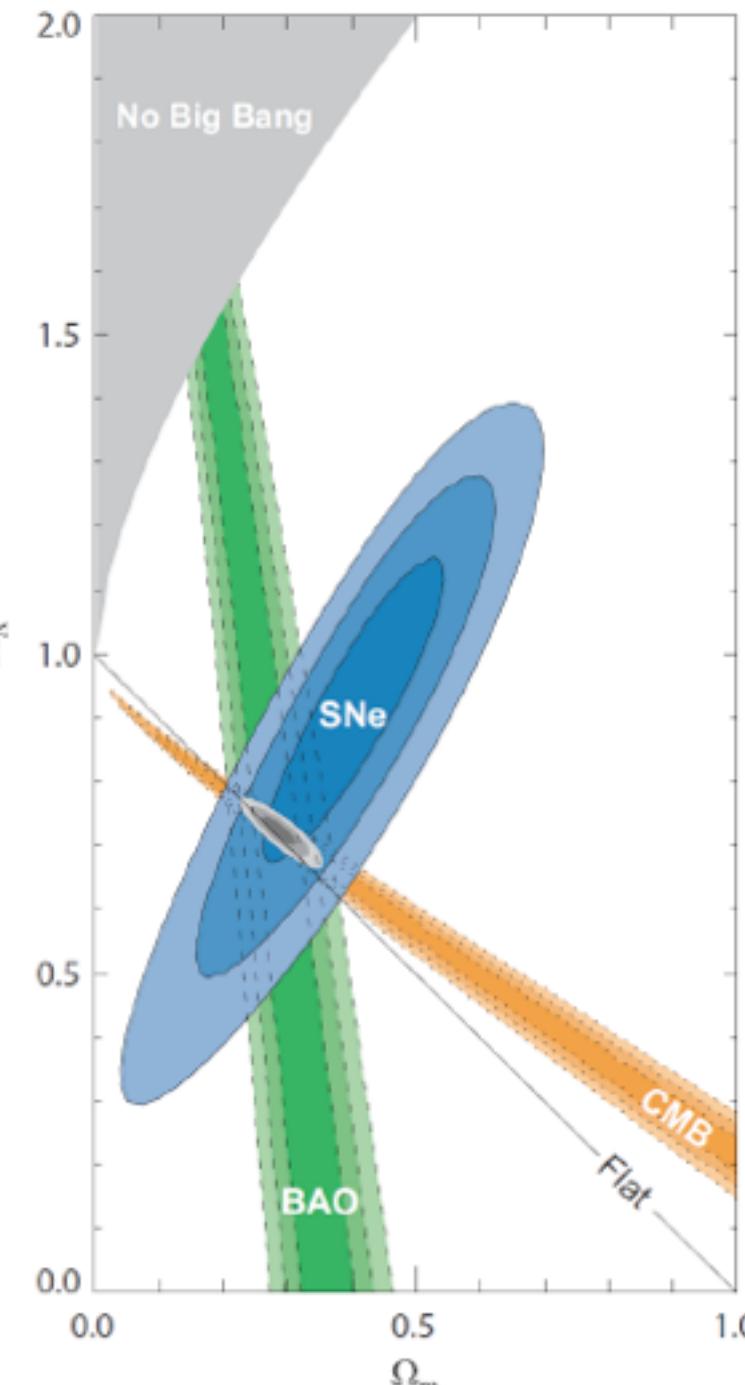
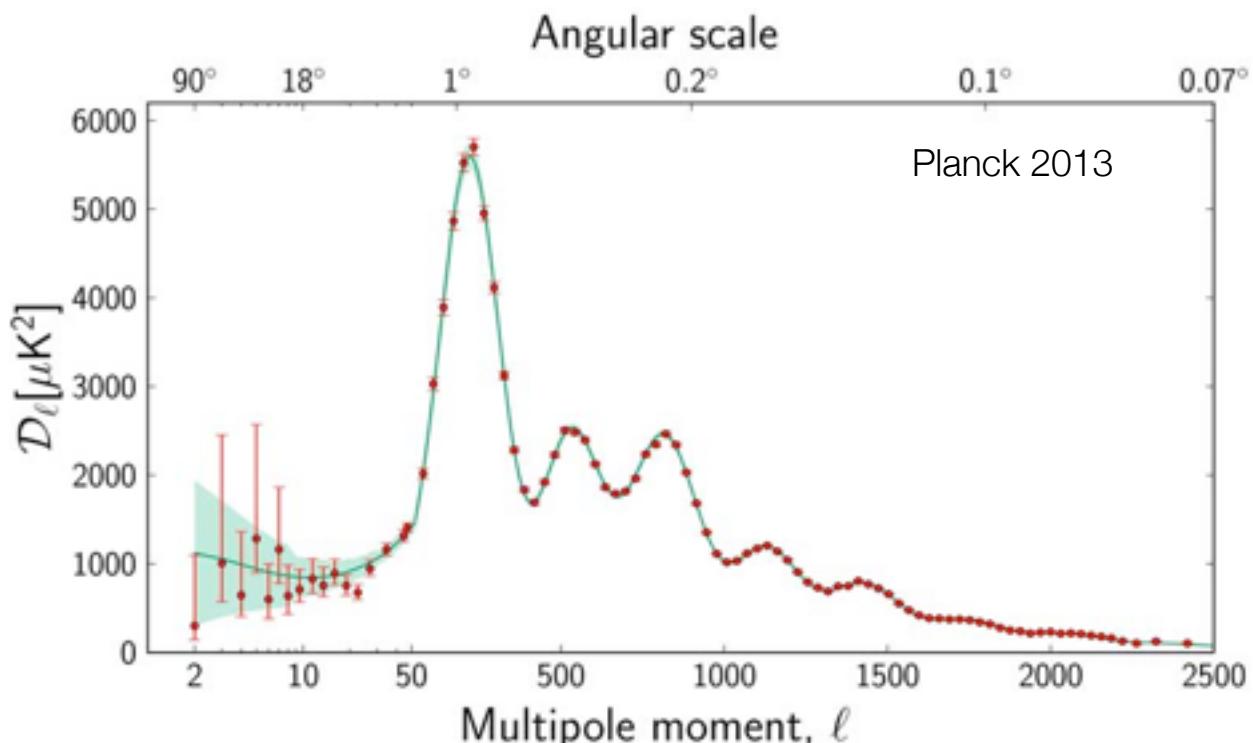
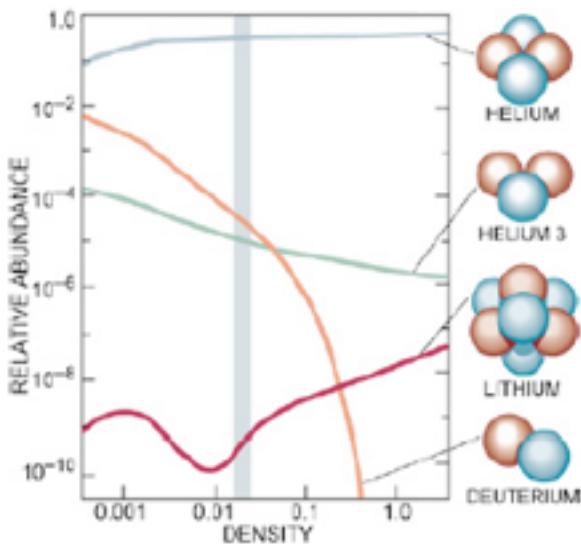
Springel, Nature (2006)

Fits to Cosmic Microwave Background

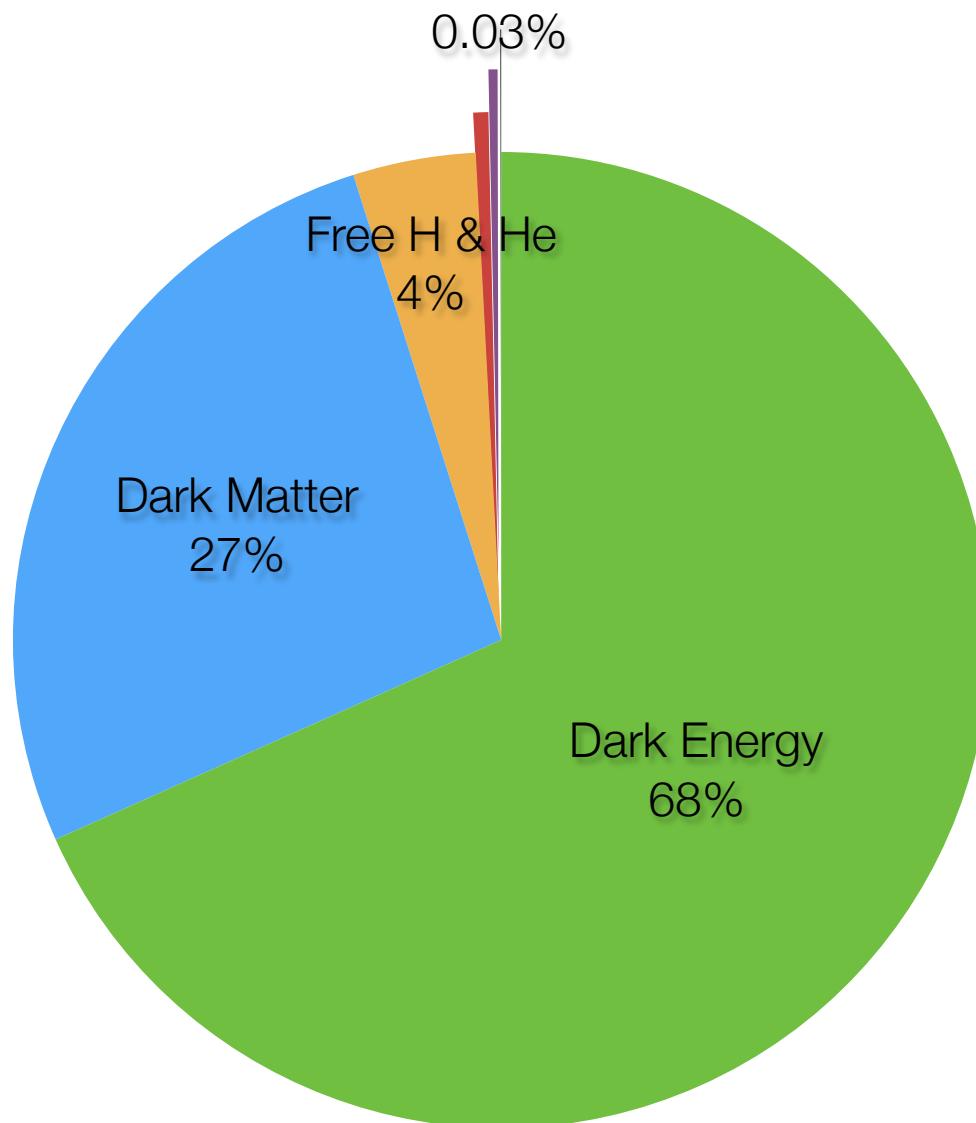


The “ Λ DM” Model of Cosmology

One model has emerged that fits all the observations with only 6 parameters.



The Λ CDM Model of Cosmology



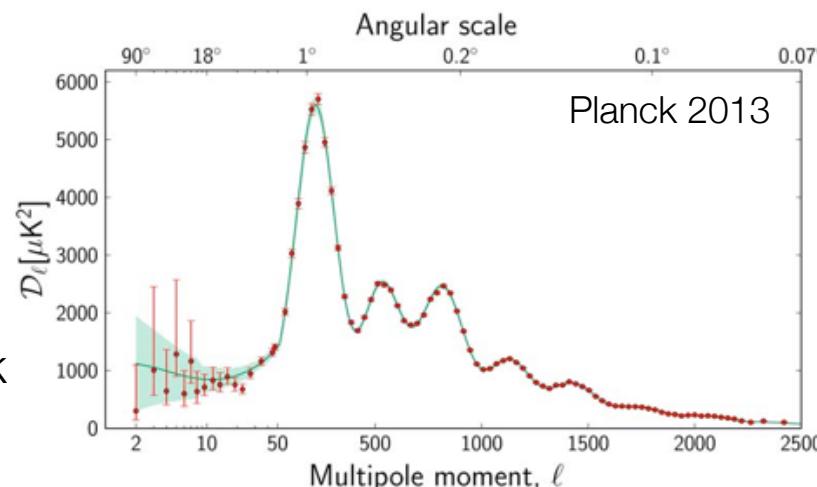
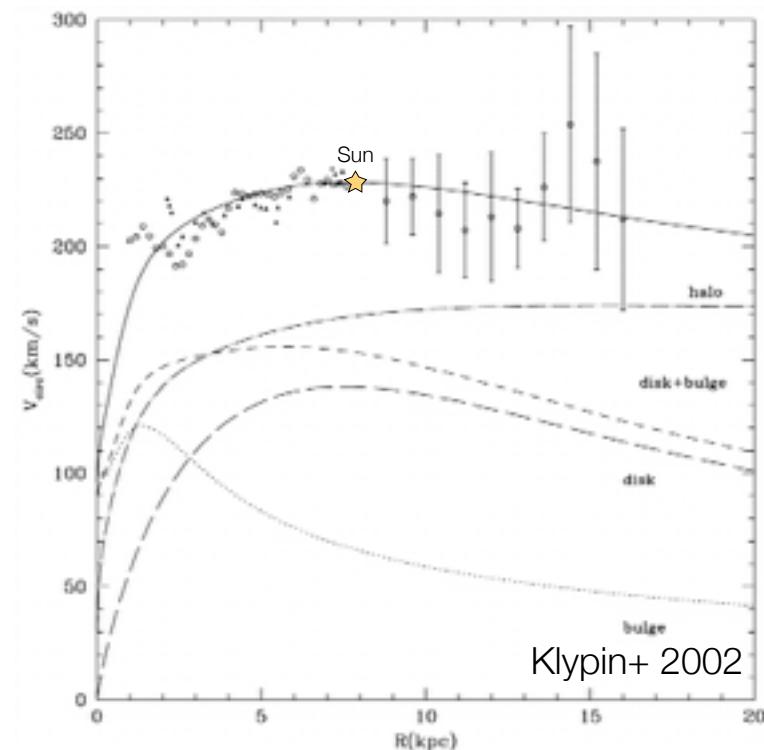
We don't know what 95% of the Universe is made of!

- This model raises some truly fundamental physics questions:
 - What is Dark Matter?
 - What is Dark Energy?

- Dark Energy
- Dark Matter
- Free H & He
- Stars and Gas
- Neutrinos
- Heavy Elements (Us)

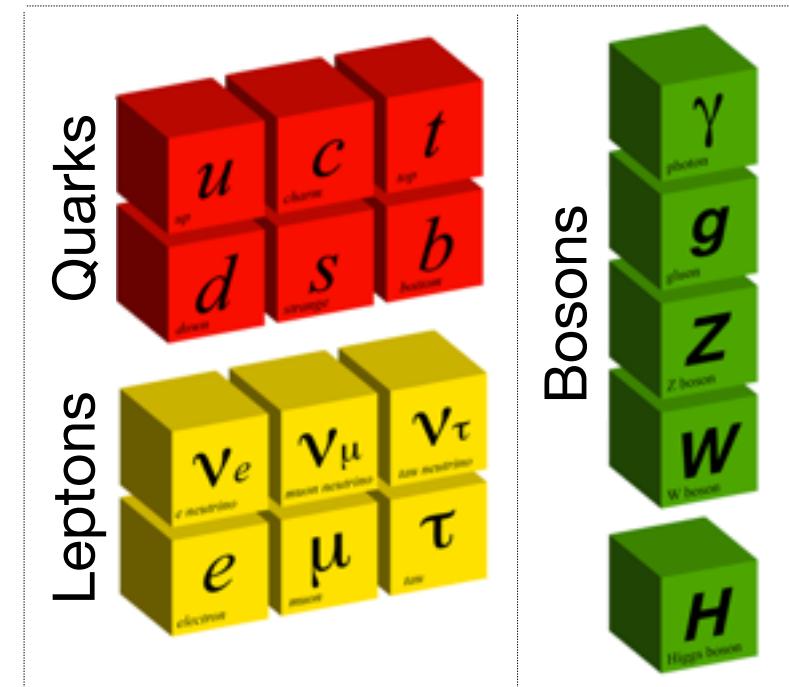
The Nature of Dark Matter

- The Missing Mass Problem:
 - Dynamics of stars, galaxies, and clusters
 - Rotation curves, gas density, gravitational lensing
 - Large Scale Structure formation
- Wealth of evidence for a particle solution
 - MOND has problems with weak lensing and CMB
 - Microlensing (MACHOs) mostly ruled out
- Non-baryonic
 - Height of acoustic peaks in the CMB (Ω_b , Ω_m)
 - Power spectrum of density fluctuations (Ω_m)
 - Primordial Nucleosynthesis (Ω_b)
- And STILL HERE!
 - Stable, neutral, non-relativistic
 - Interacts via gravity and (maybe) some sub-weak scale force

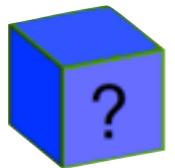


Dark Matter may be a Rosetta Stone!

We know the Standard Model is incomplete.



Where does dark matter fit in?

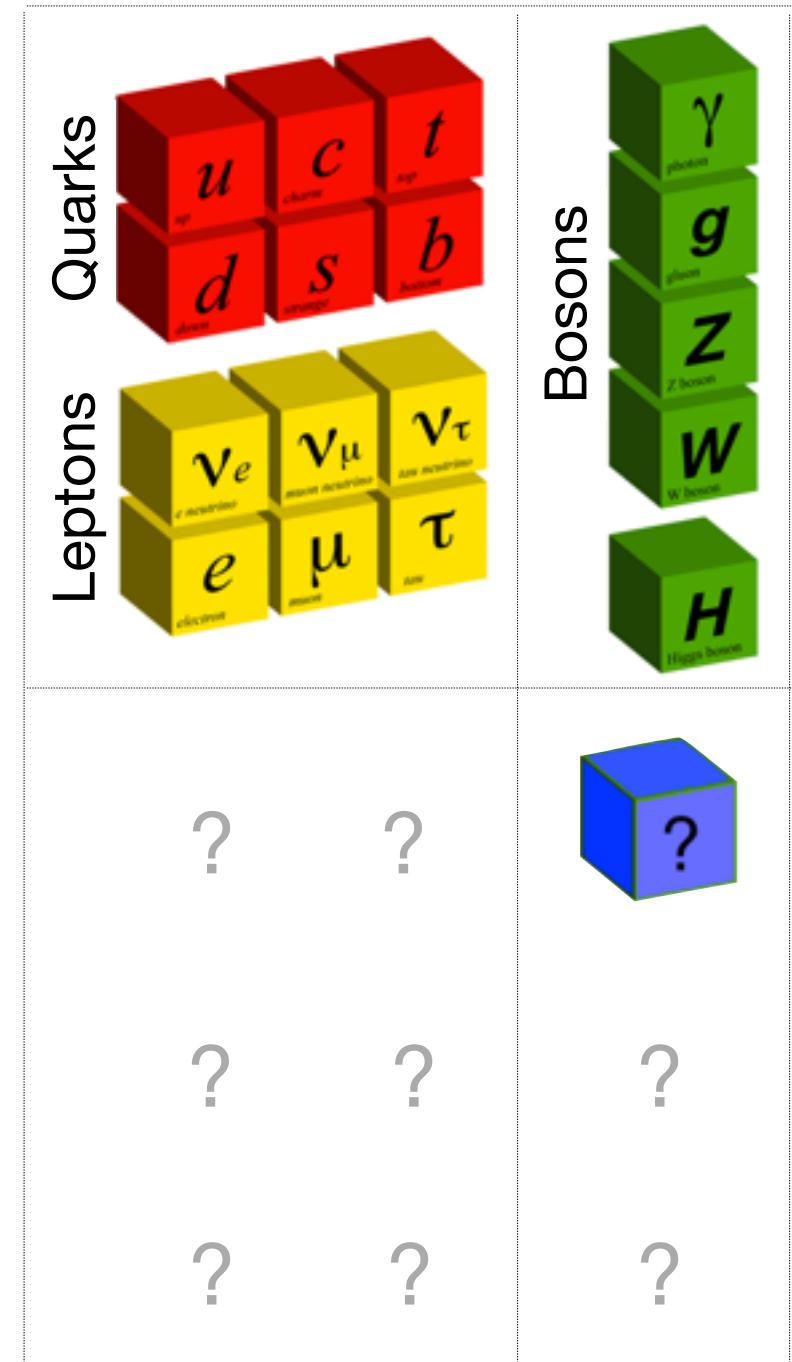


Dark Matter may be a Rosetta Stone!

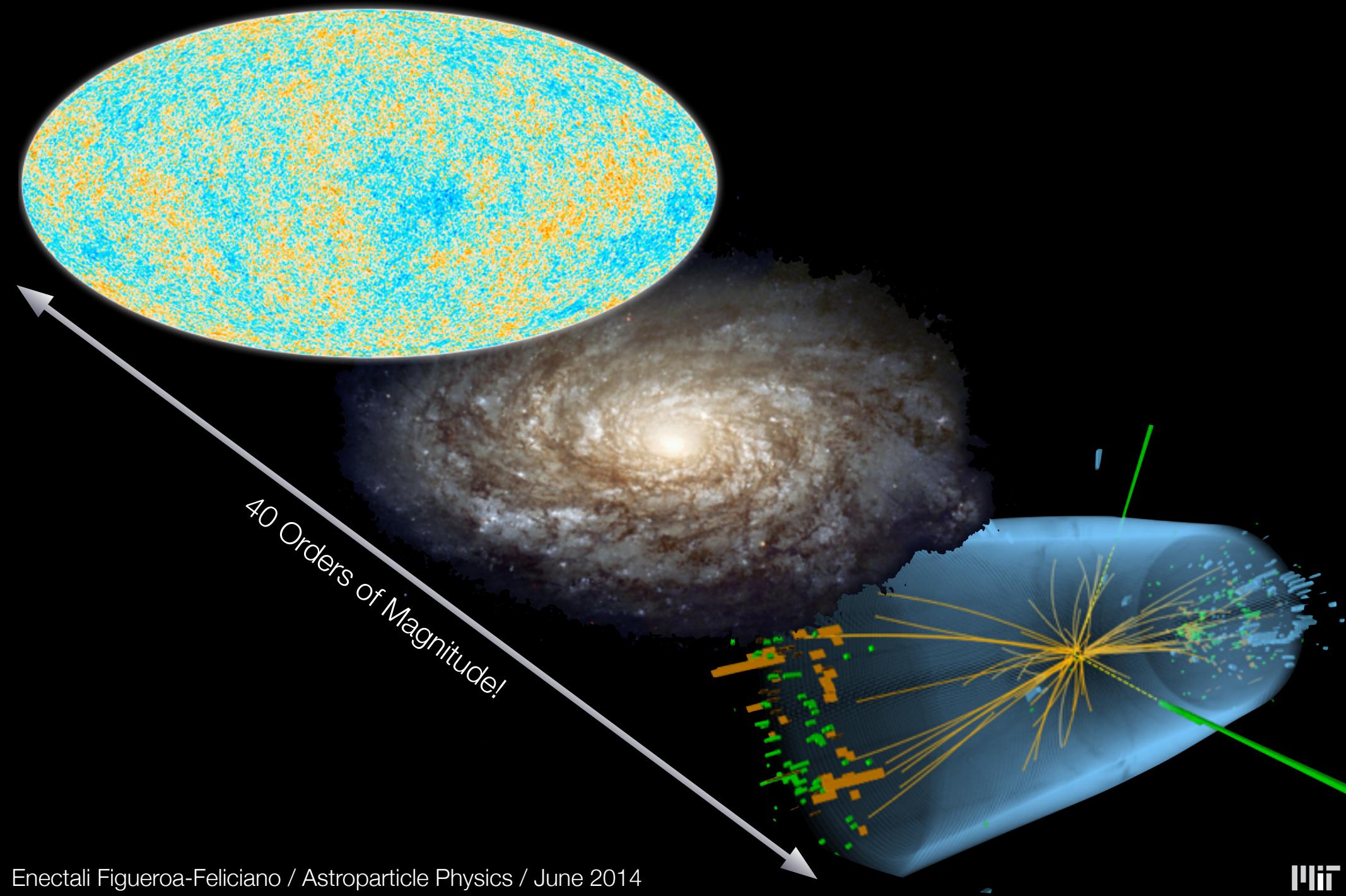
We know the Standard Model is incomplete.

Where does dark matter fit in?

And how does it fit into a more general understanding?



A Beautiful Problem in Physics



MSSM

R-parity
violating

NMSSM



Dark Messages from the LHC

Tim Tait

Thursday 09:30 - 10:00

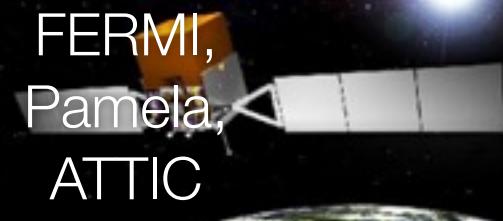


T Tait

The Hunt for Dark Matter



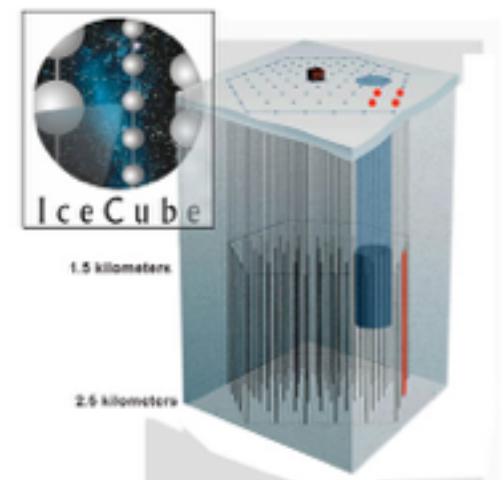
AMS-02



FERMI,
Pamela,
ATTIC



HESS, VERITAS,
Magic



1.5 kilometers

2.5 kilometers

Annihilation
or Decay in
the Cosmos



Astrophysics
Measurements

15



LHC

Production in
Colliders



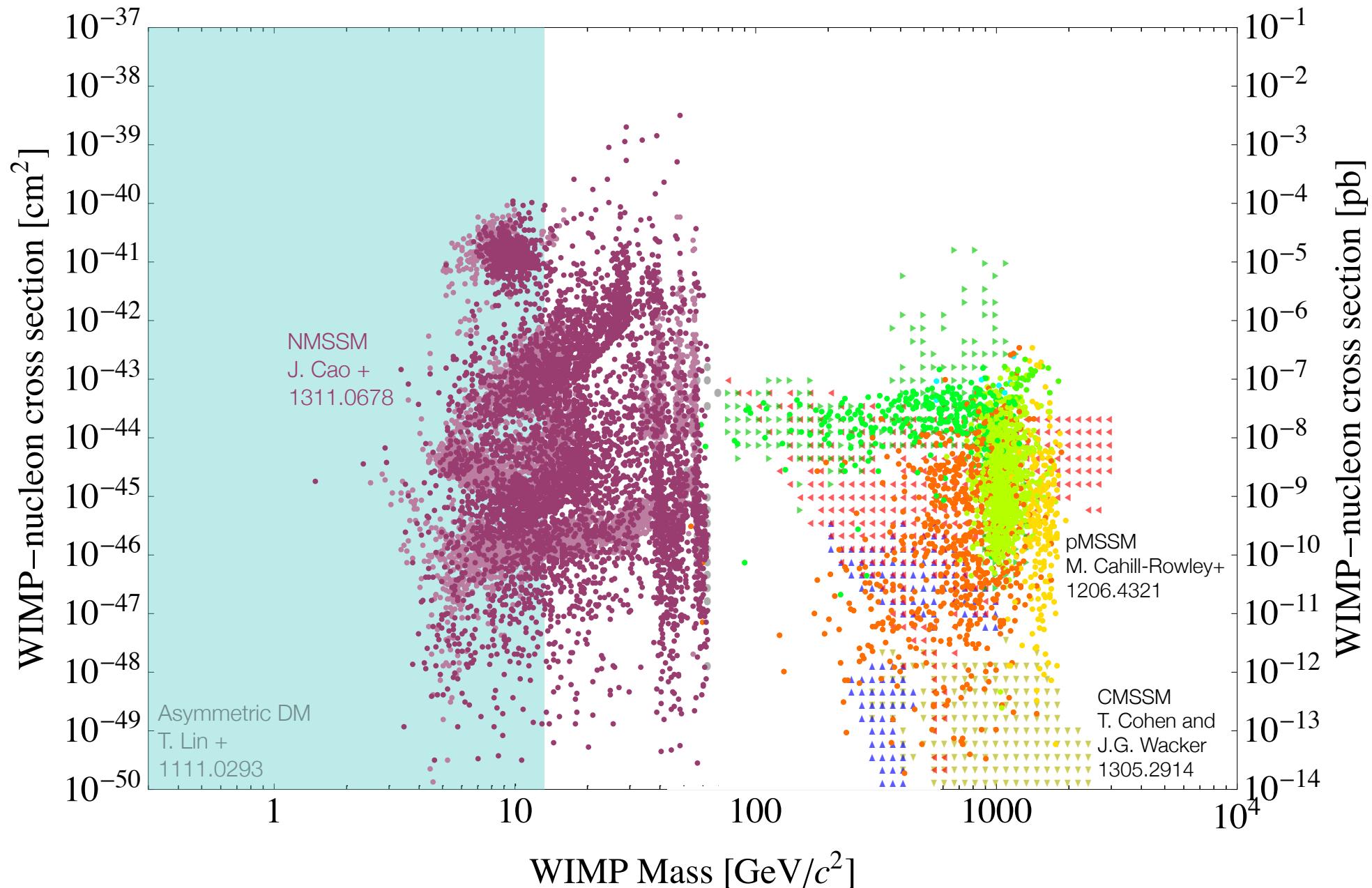
SuperCDMS



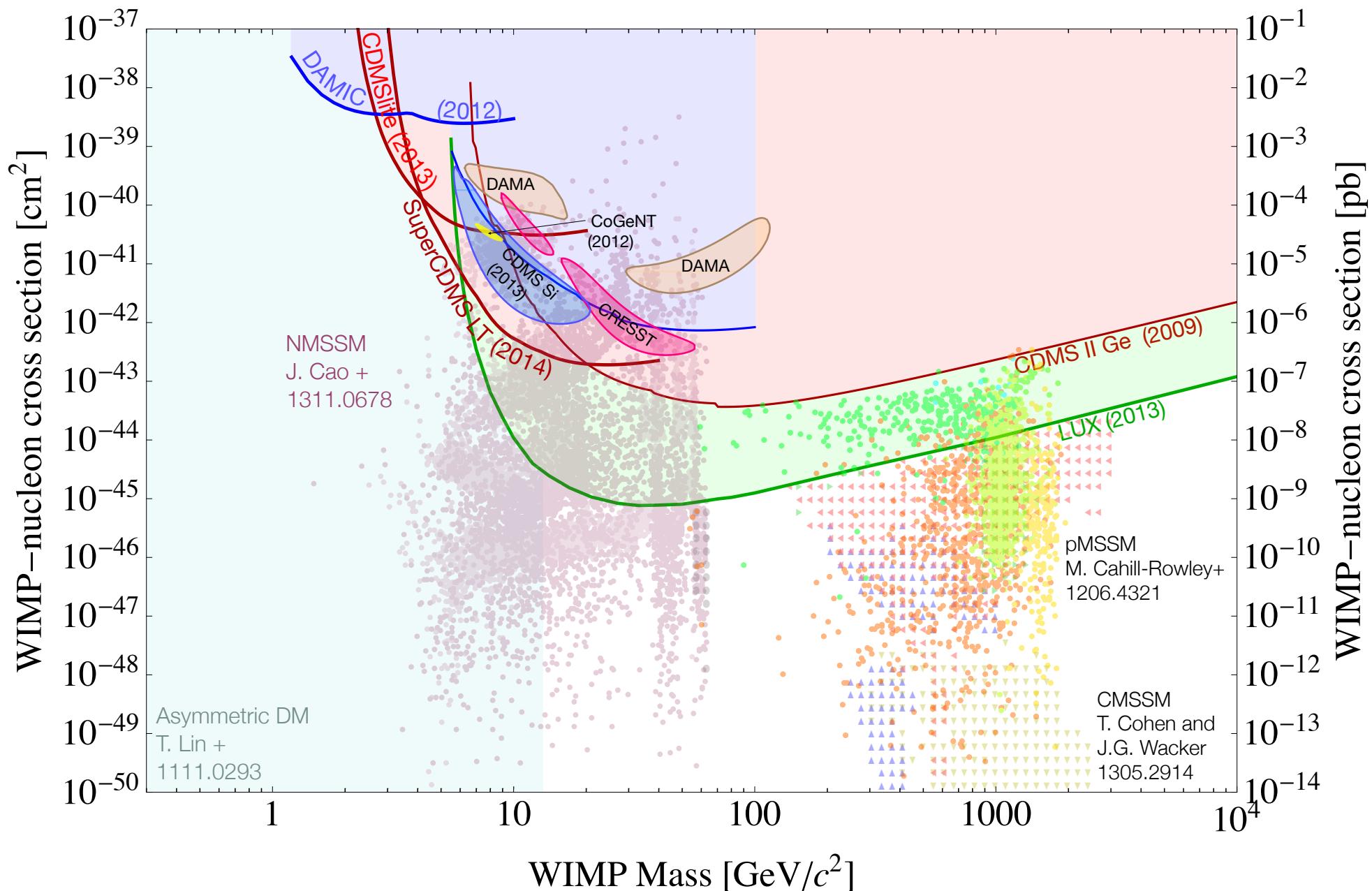
LUX

Direct Detection

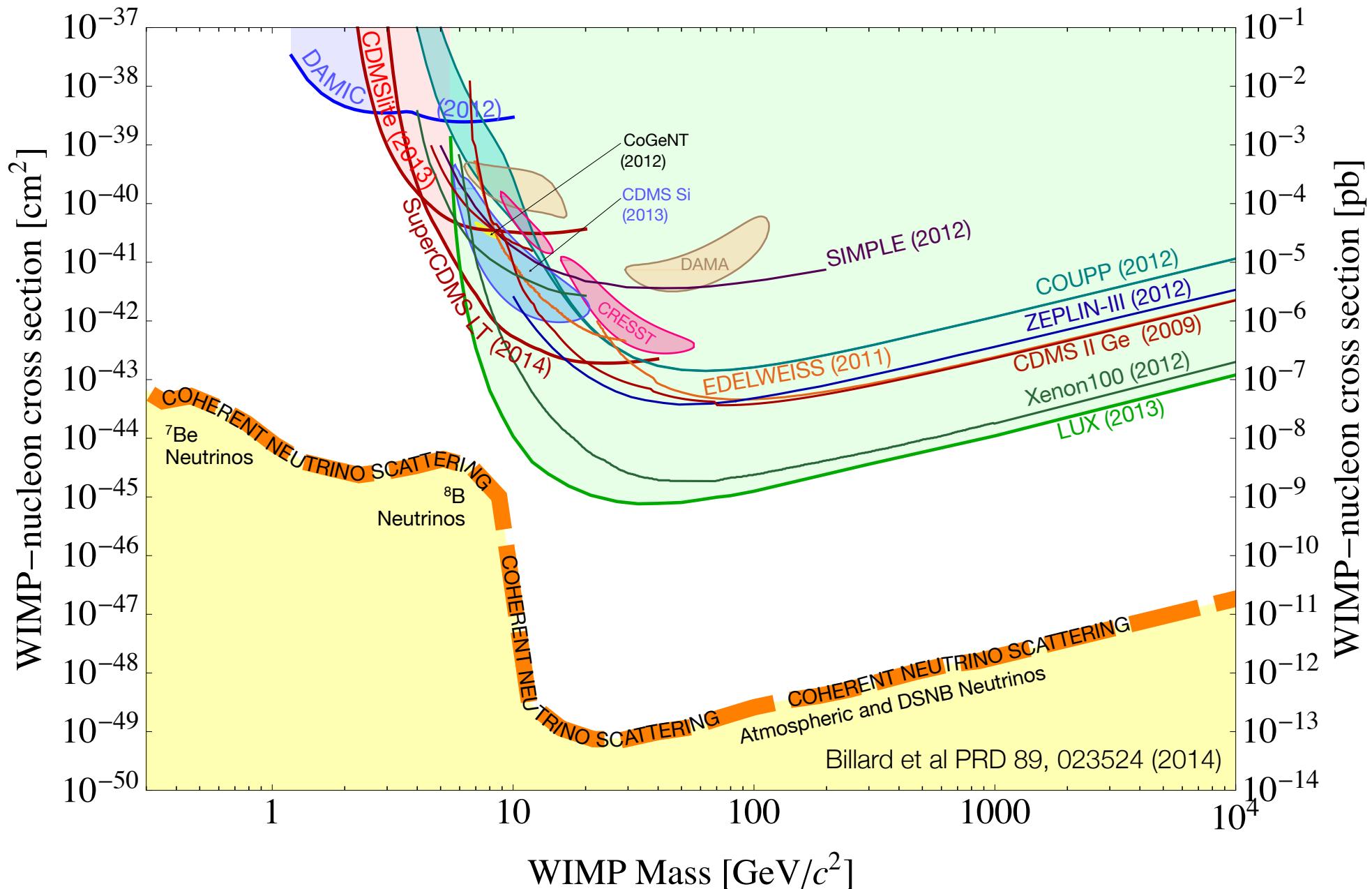
The Playing Field



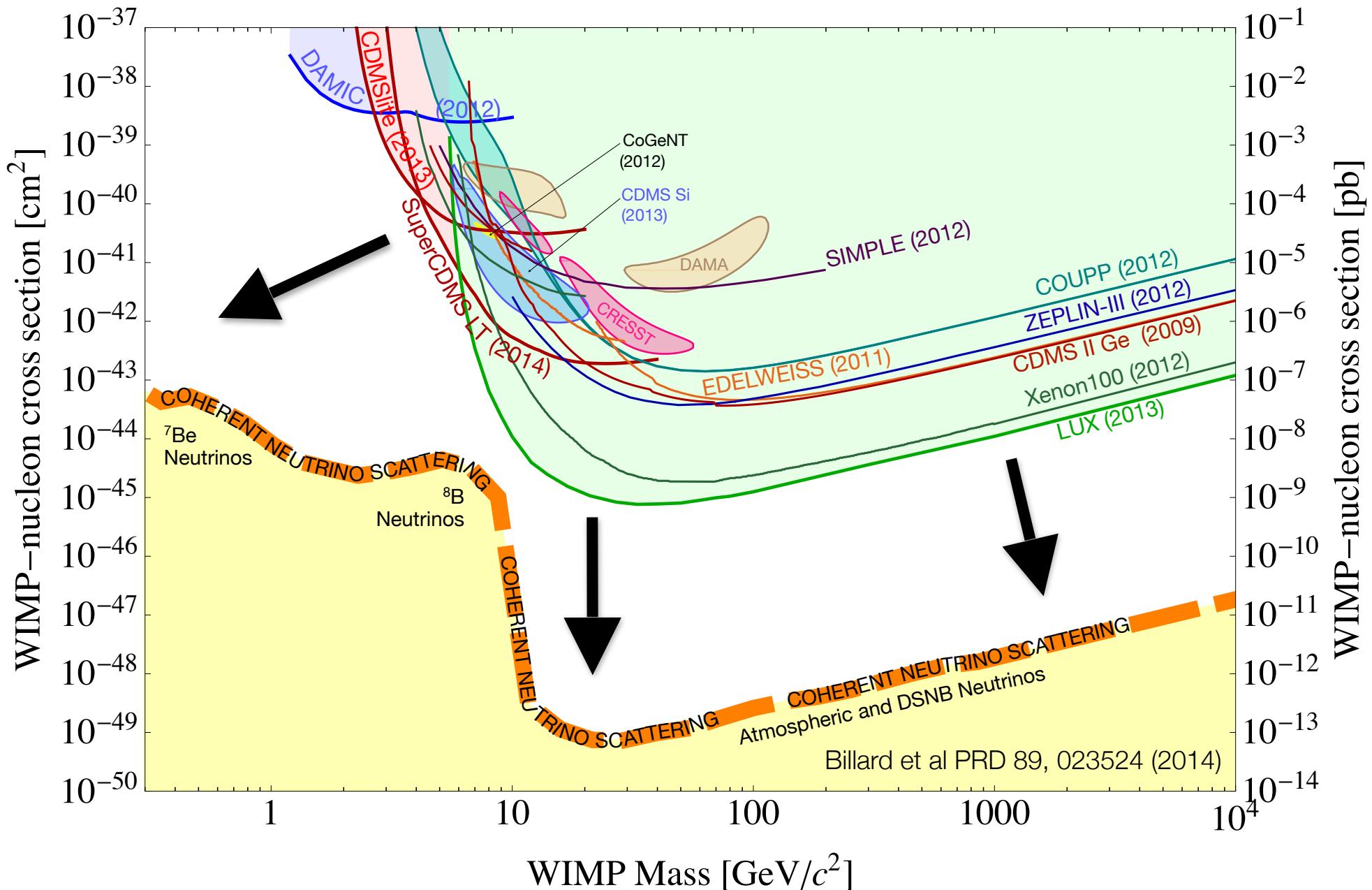
Some current limits by target...



Where should we search?



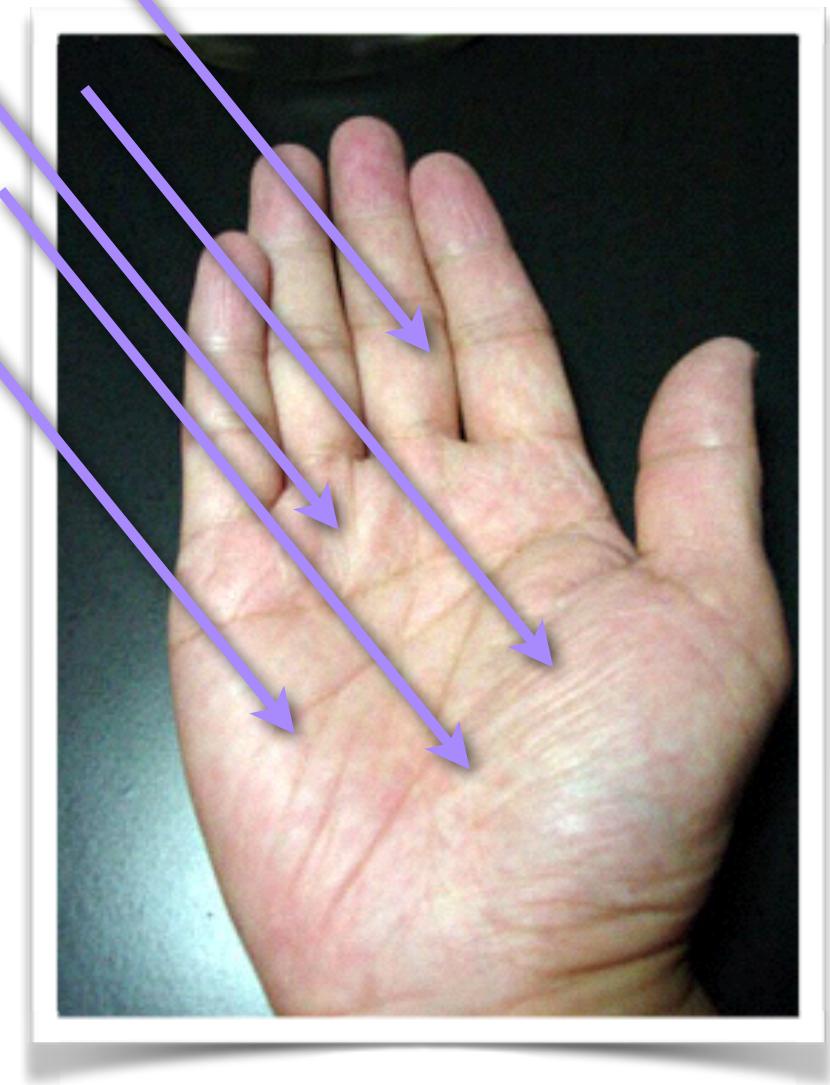
Everywhere!



Dark Matter in the Lab



- Assume a Maxwell-Boltzmann velocity distribution for the dark matter halo
- Density: 0.3 GeV/cm^3
- Mass: assume $60 \text{ GeV}/c^2$
- Relative velocity $\sim 220 \text{ km/s}$
- $\sim 100,000 \text{ particles}/\text{cm}^2/\text{sec}$
- About 20 million/hand/sec



Principles of Particle Detection

	particle theory	nuclear structure	astrophysics properties
Interaction Rate [events/keV/kg/day]	$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi}$	$\frac{F^2(E_R)}{m_r^2}$	$\frac{\rho_o T(E_R)}{v_o \sqrt{\pi}}$

$$F(E_R) \simeq \exp(-E_R m_N R_o^2/3)$$

“form factor” (quantum mechanics of interaction with nucleus)

$$m_r = \frac{m_\chi m_N}{m_\chi + m_N}$$

“reduced mass”

$$T(E_R) = \frac{\sqrt{\pi}}{2} v_o \int_{v_{\min}}^{\infty} \frac{f_1(v)}{v} dv$$

integral over local WIMP velocity distribution

$$v_{\min} = \sqrt{E_R m_N / (2m_r^2)}$$

minimum WIMP velocity for given E_R

WIMP-Nucleus Interaction: The Standard Assumptions

- Spin-Independent:

- The scattering amplitudes from individual nucleons interfere.
- For zero momentum transfer collisions (extremely soft bumps) they add coherently:

$$\sigma_o \simeq \frac{4m_r^2}{\pi} f A^2$$

↑
coupling constant

← atomic mass

Enormous enhancement for
heavy nuclei target!

$$m_r = \frac{m_\chi m_N}{m_\chi + m_N} \quad = \text{"reduced mass"}$$

- Spin-Dependent:

- Dominated by unpaired nucleons
- For spinless nuclides, SD cross section = 0
- For zero momentum transfer collisions (extremely soft bumps) the cross section is approximately:

$$\sigma_o = \frac{32(J+1)}{\pi J} G_F^2 m_r^2 (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2$$

↑ ↑ ↑ ↑
Nuclear Angular Momentum Fermi constant Coupling constant Spin

WIMP-Nucleus Interaction: maybe not so simple?



Model Independent Bounds in Direct
Dark Matter Searches
Paolo PANCI Friday 17:10 - 17:30

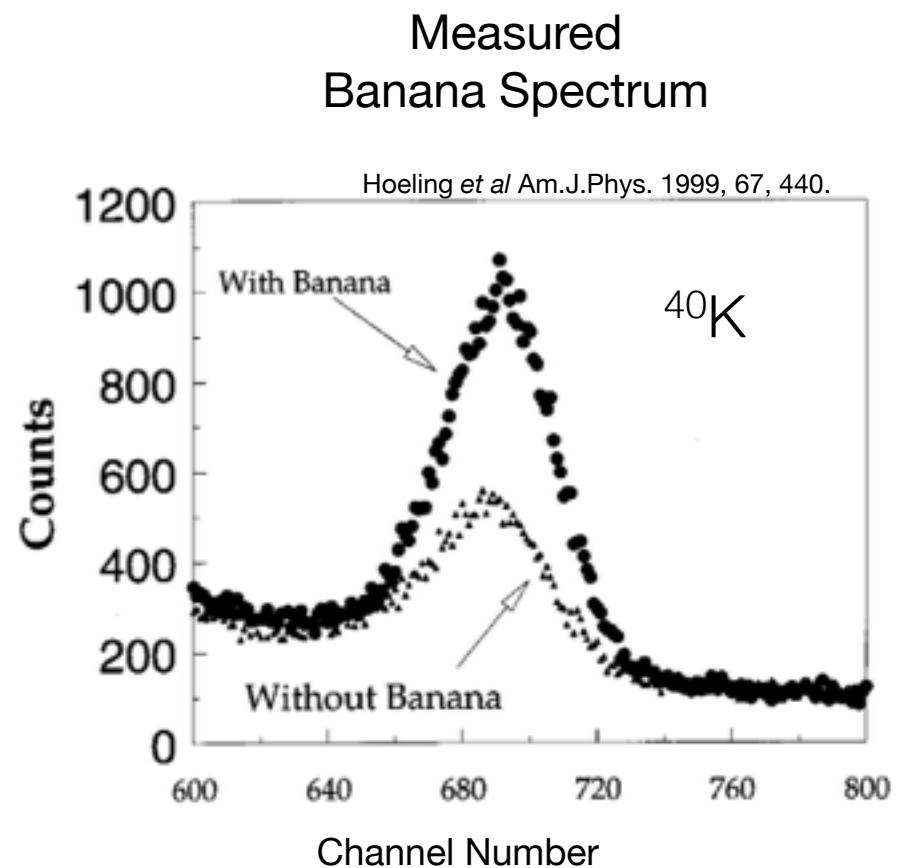
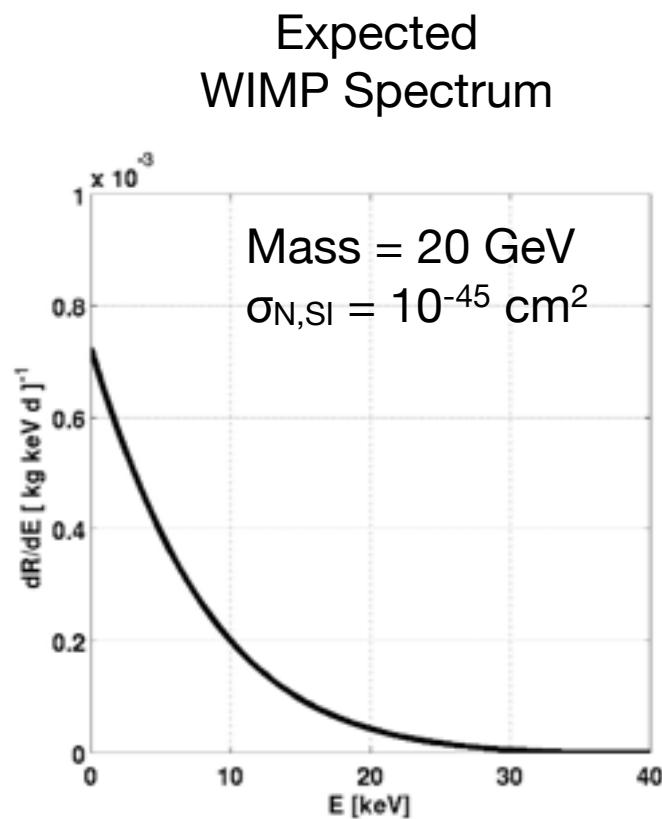
- Effective WIMP-nucleon cross section depends on six independent nuclear response functions:
 - One “Spin independent”
 - Two “Spin Dependent”
 - Three “Velocity-Dependent”
- Two pairs of these interfere, so there are *eight independent parameters* that can be probed
- Take home message: *We will need multiple targets to map out the physics of WIMP-nucleon interactions!*

The effective field theory of dark matter direct detection

A. Liam Fitzpatrick,^a Wick Haxton,^b Emanuel Katz,^{a,c,d}
Nicholas Lubbers,^c Yiming Xu^c

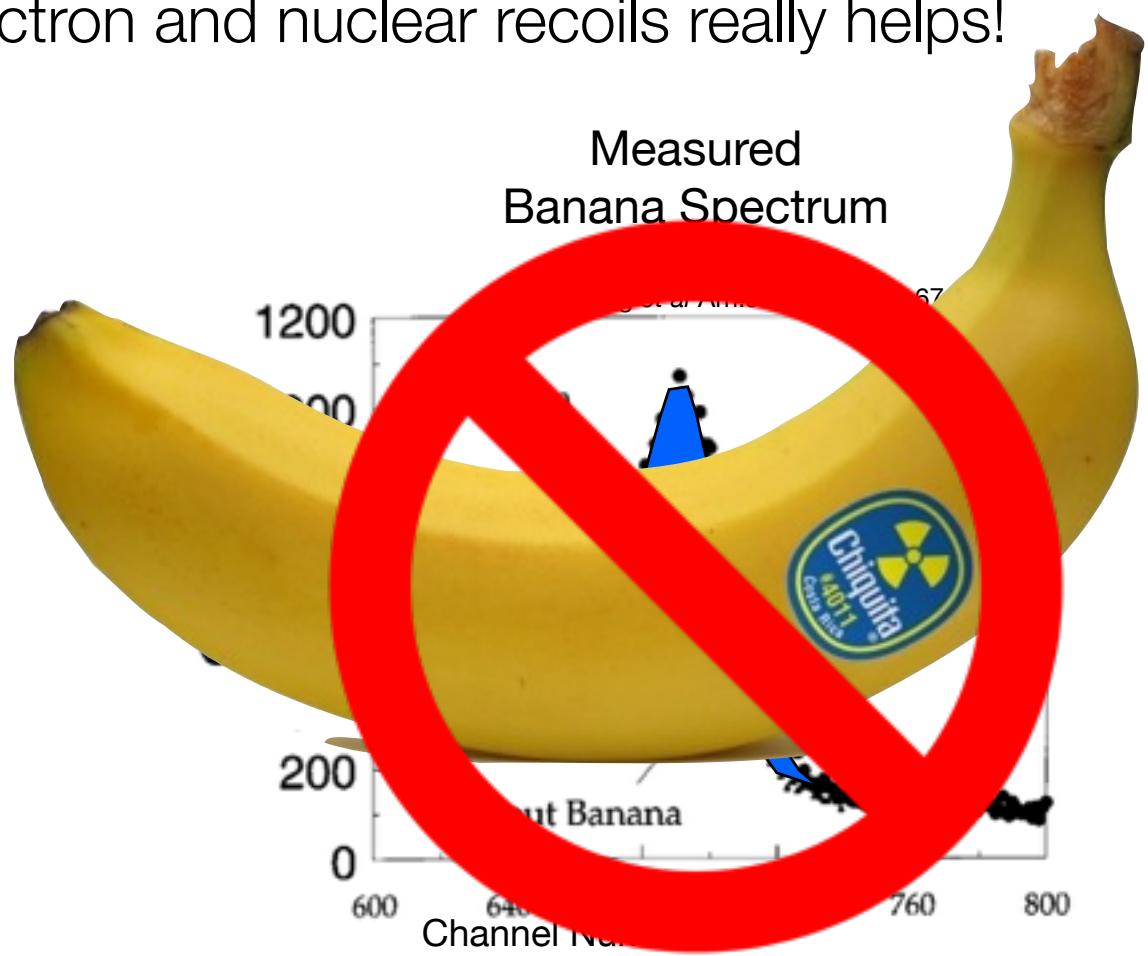
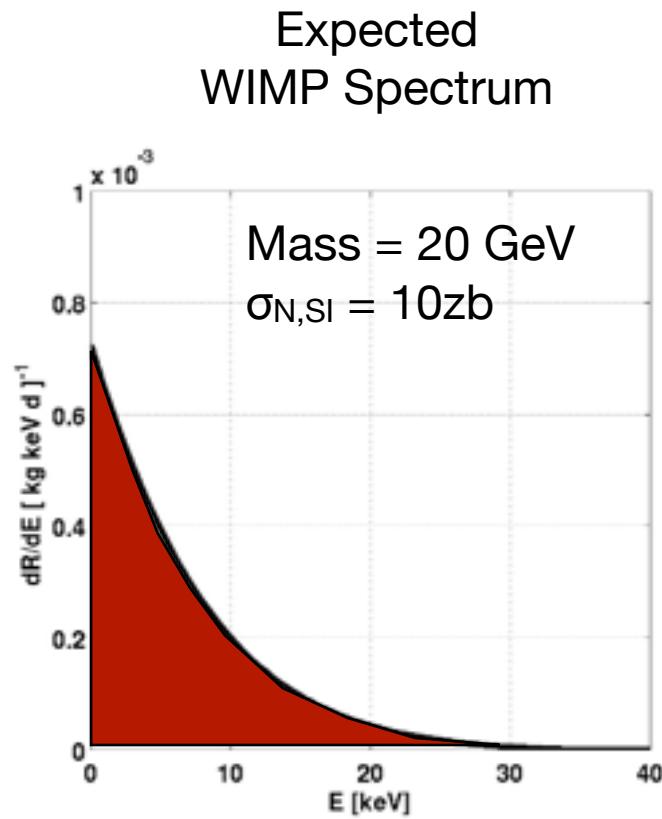
<http://arxiv.org/abs/1211.2818>
<http://arxiv.org/abs/1308.6288>
<http://arxiv.org/abs/1405.6690>

The Interaction Rate is Extremely Low!



But the Interaction Rate is Extremely Low!

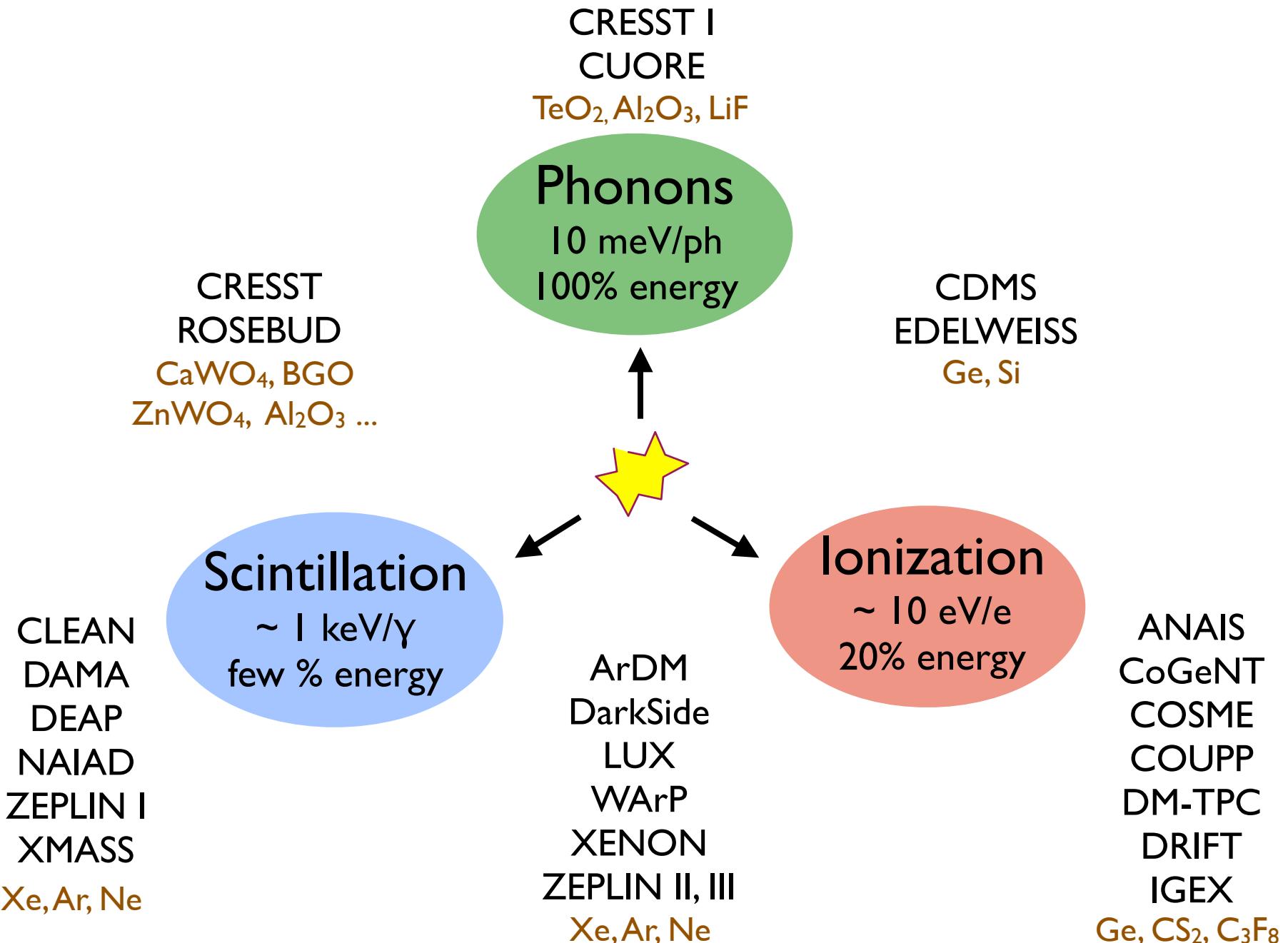
Discrimination between electron and nuclear recoils really helps!



~1 event per kg per **year**
(Nuclear Recoils)

~100 event per kg per **second**
(Electron Recoils)

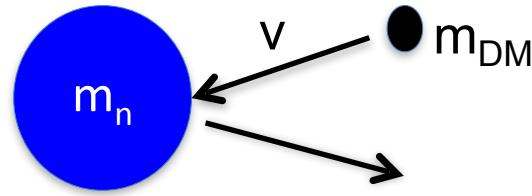
Electron/Nuclear recoil discrimination



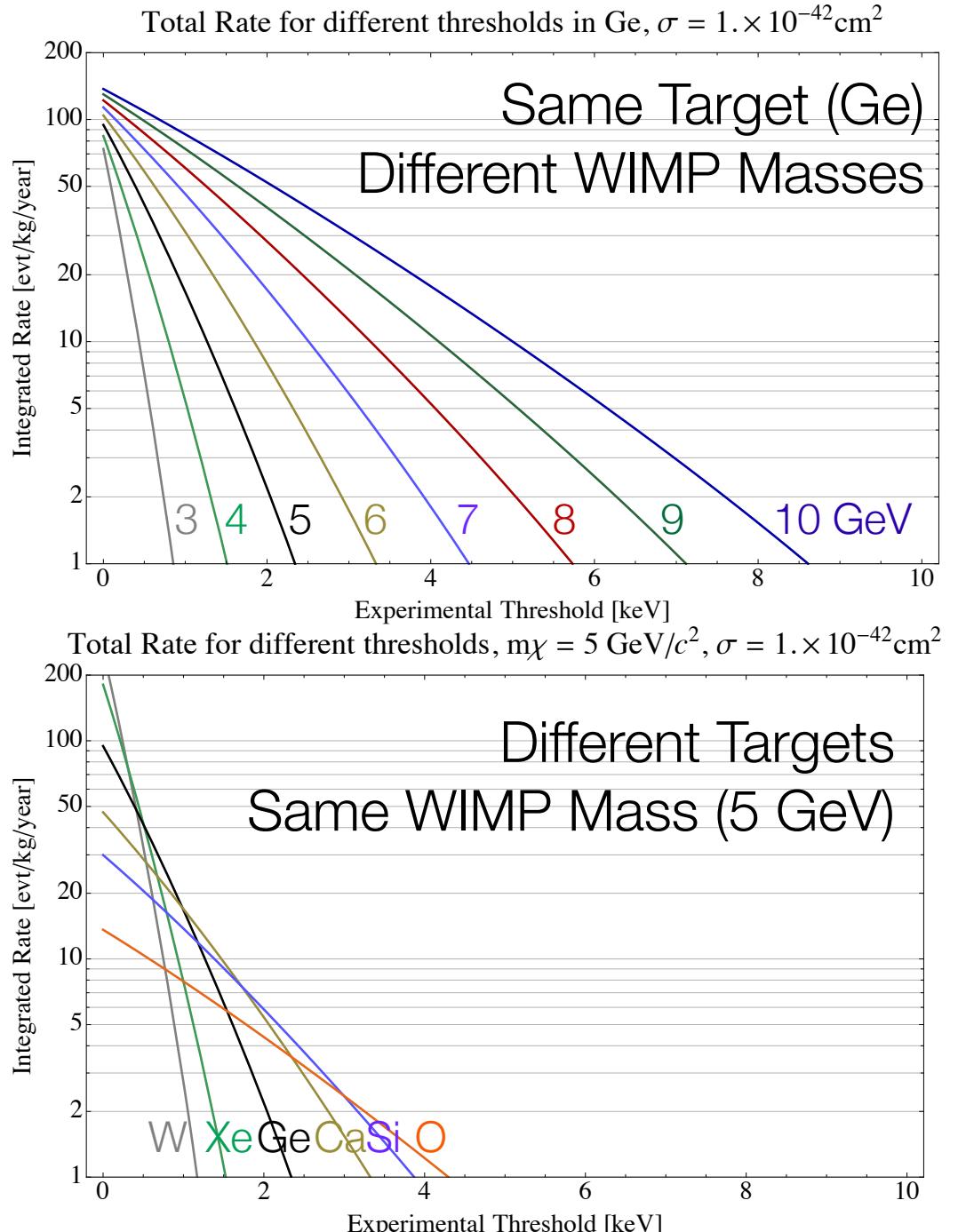
Thinking outside the Triangle...

- Scintillation Timing (DEAP/CLEAN)
- Signal Modulation (DAMA/LIBRA, DRIFT, DM-TPC, etc...)
- Nuclear-recoil-only trigger mechanism
 - (a la COUPP, PICASSO, PICO...)
- Self-Shielding (XMASS)
- Others...

The low-mass WIMP challenge



$$\Delta E = \frac{\Delta P^2}{2M_n} \lesssim \frac{2M_{DM}^2 v^2}{M_N}$$

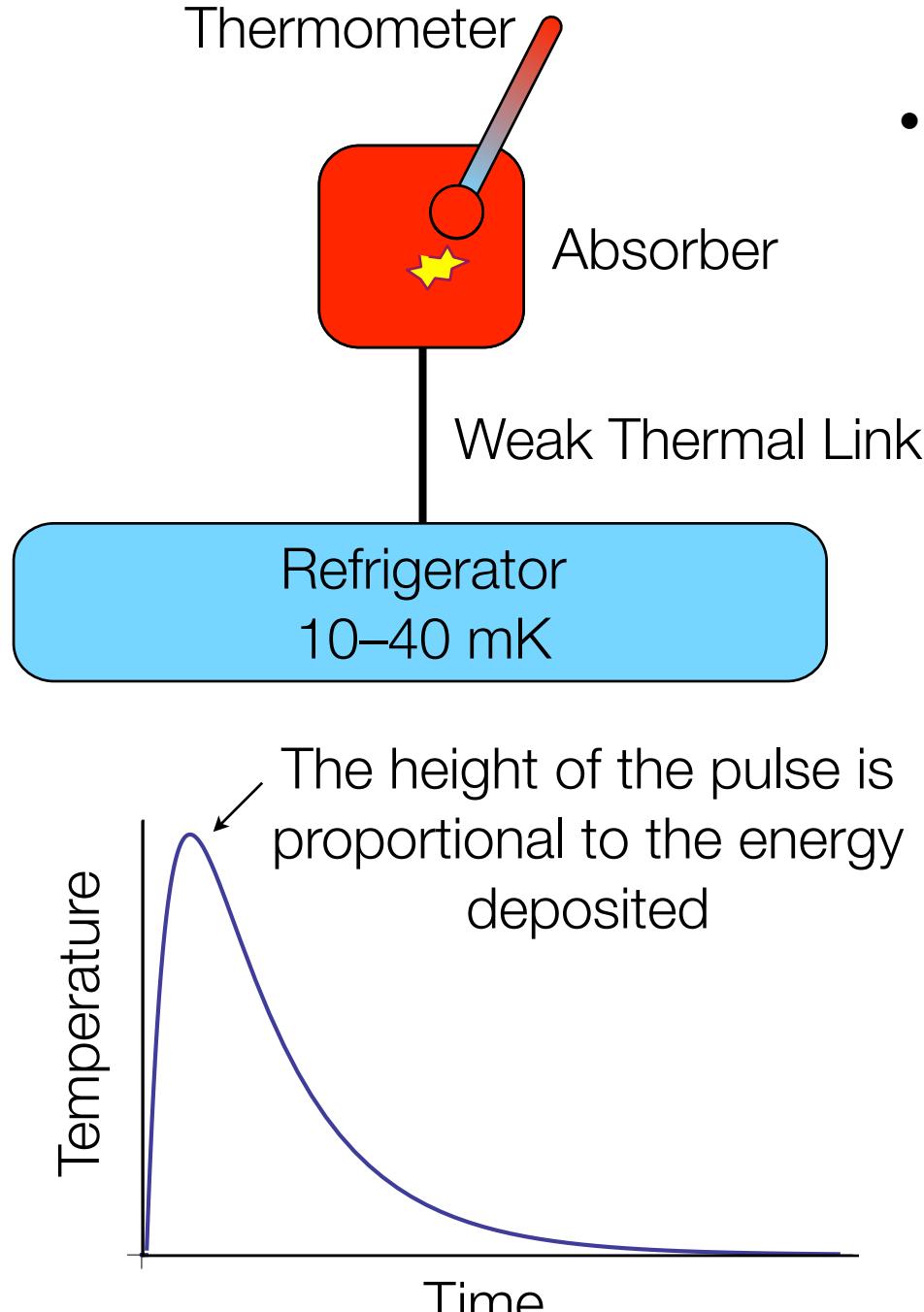


Summary of Direct Detection Requirements

- 1: Large Exposure (Mass x Time)
- 2: Low Background Rate
- 3: Discrimination between Signal and Backgrounds
- 4: Low Energy Threshold

Cryogenic Crystal Detectors

Phonon Readout

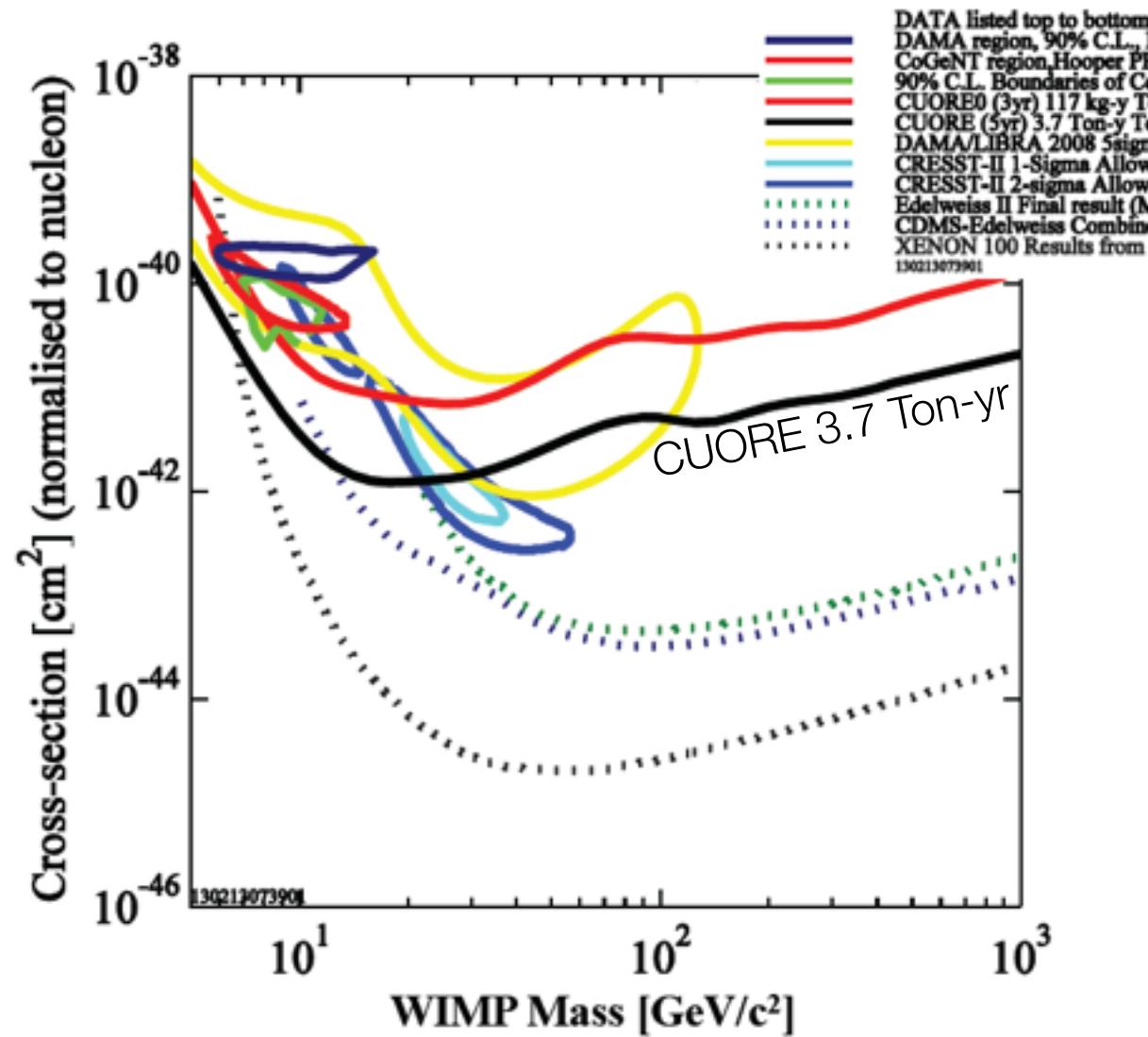
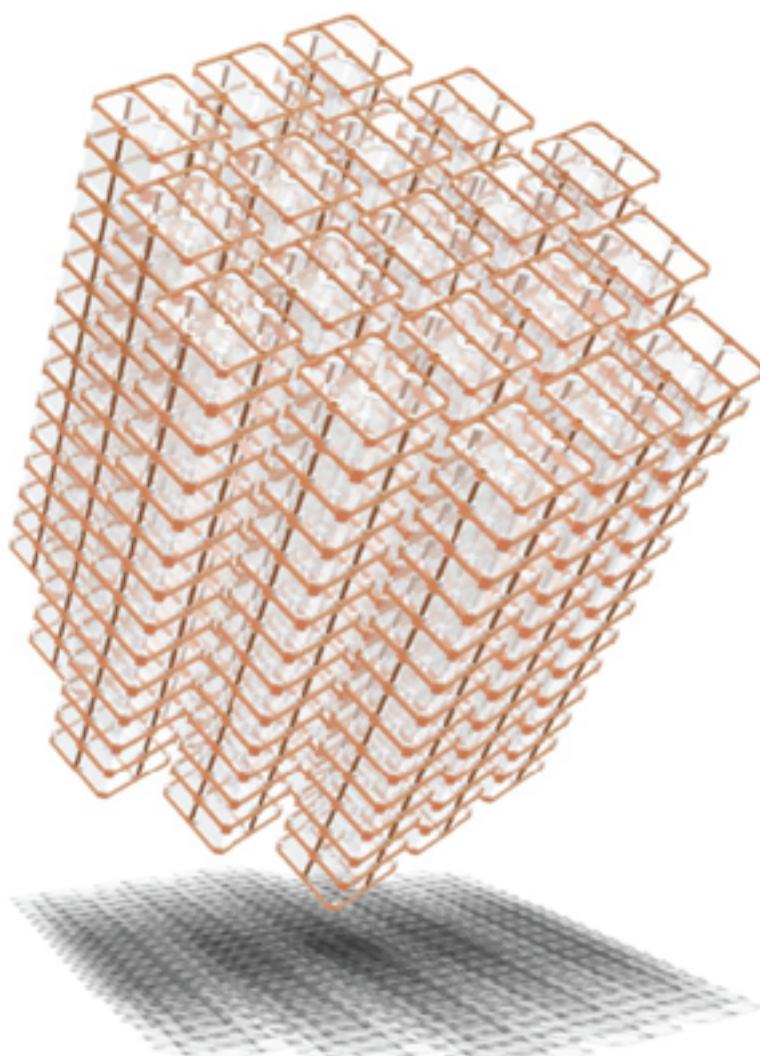


- Advantages of phonon readout:
 - Direct measurement of nuclear recoil energy; no quenching factors involved
 - ~100% of the recoil energy is sensed, allowing for low thresholds
 - Good energy resolution near threshold, allowing for better determination of WIMP recoil spectrum once a signal is seen
 - Low threshold enables sensitivity to lower WIMP masses + larger rate/kg for large WIMP masses.

CUORE: Phonon Readout Only



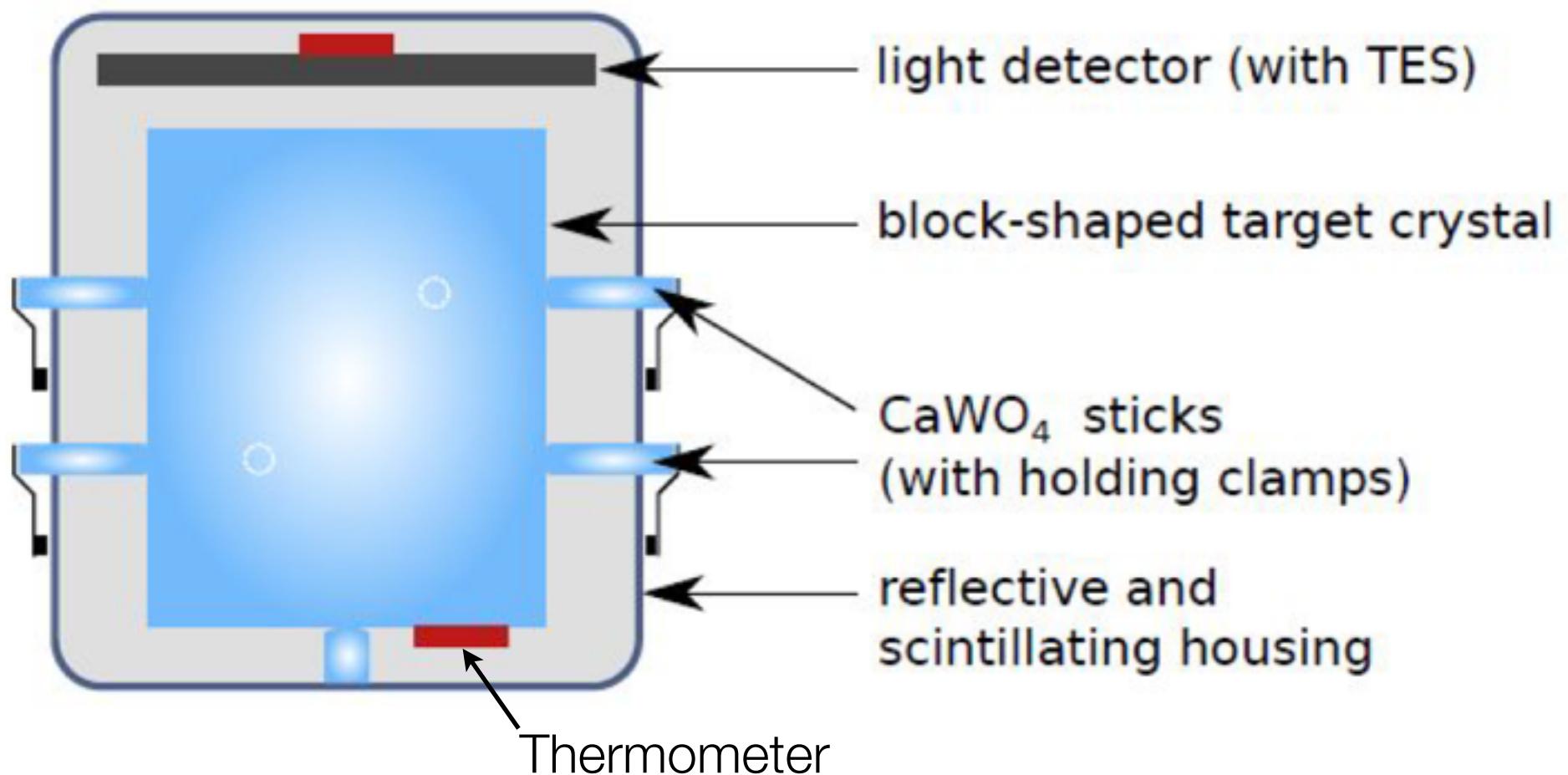
Neutrinoless double beta decay and dark matter searches with CUORE-0 and CUORE
Maria MARTINEZ Thursday 17:30 - 17:50



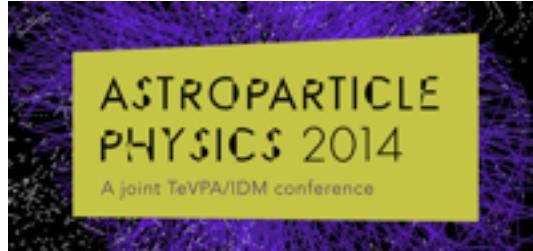
CRESST: Phonon + Scintillation Light



New Results from the CRESST Experiment
Raimund STRAUSS
Monday 17:50 - 18:10



CRESST: Phonon + Scintillation Light



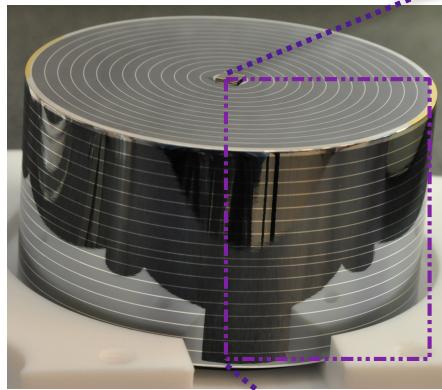
New Results from the CRESST Experiment
Raimund STRAUSS
Monday 17:50 - 18:10

- Surface alpha background greatly reduced
- Much more radiopure crystals
- Very low threshold WIMP search
- Present run data blinded
- Will present results from first unblinded period on low mass wimps + future projections!

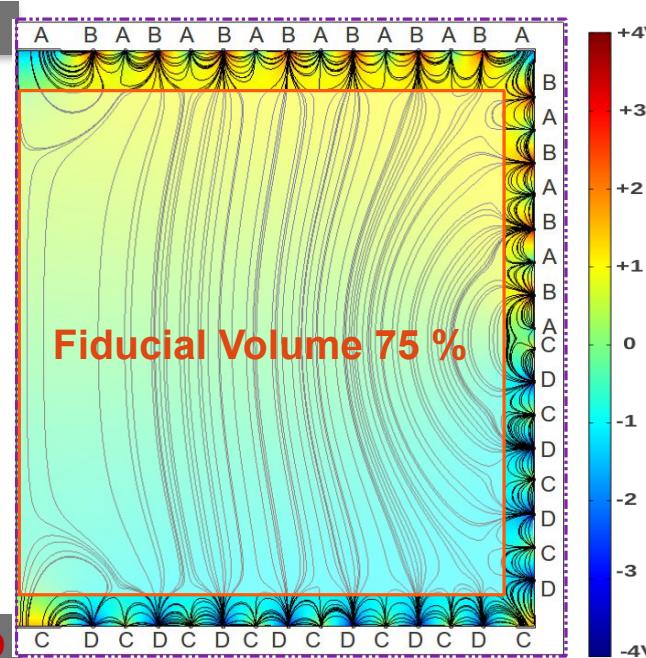


EDELWEISS: Phonon + Charge

Height : 4cm



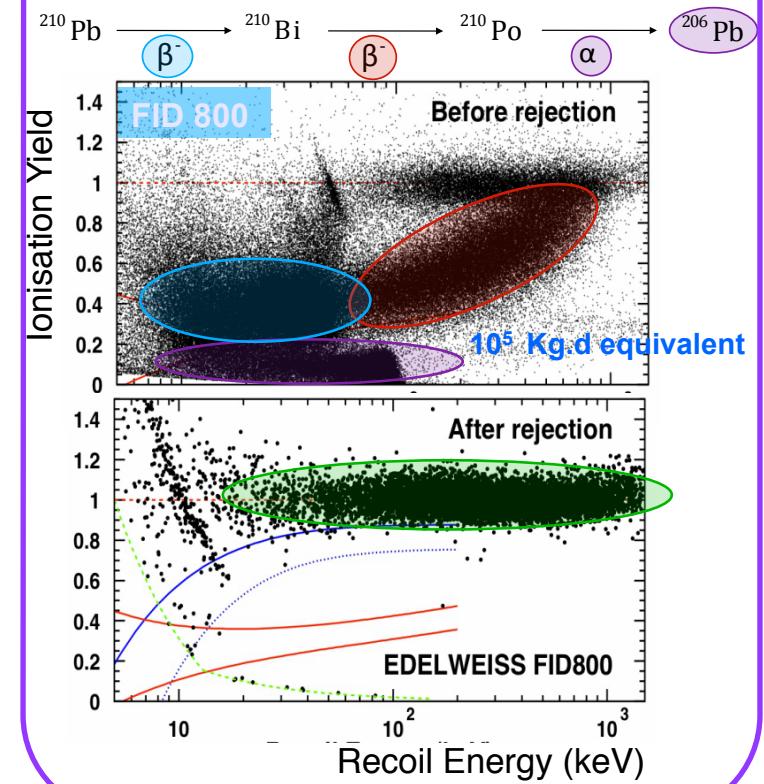
Width : 7cm



Full Inter-Digitized 800g
HP-Ge Detector

FID Surface Rejection

$4 \cdot 10^{-5}$ misidentified events/(kg.d)
(90% CL, $\text{Er} > 15 \text{ keV}$)



EDELWEISS: Phonon + Charge



The EDELWEISS III Experiment
Silvia SCORZA
Friday 14:30 - 14:50

Current Status

36 x 800 g detectors installed
in cryostat

More than 20 kg of fiducial
mass in germanium

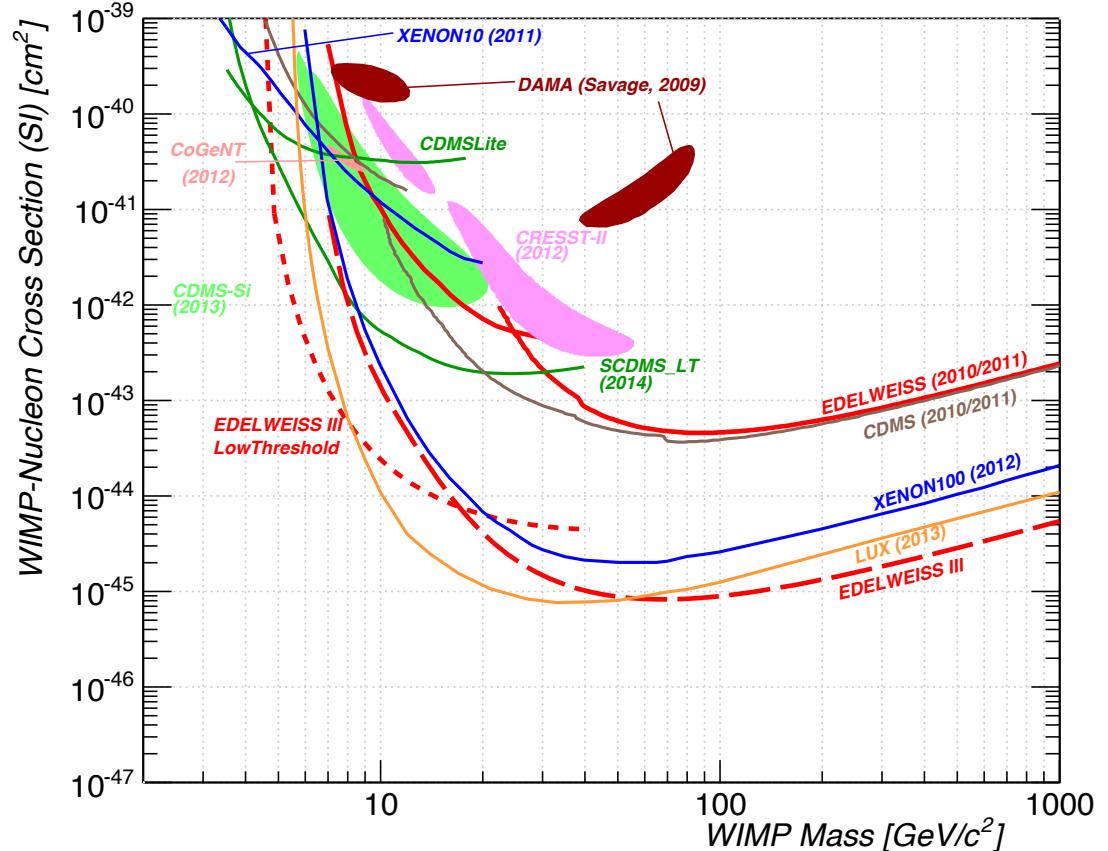
Timeline

End of 2014/ Early 2015

Reach 3000 kg.d
(6 months of data taking)

2016

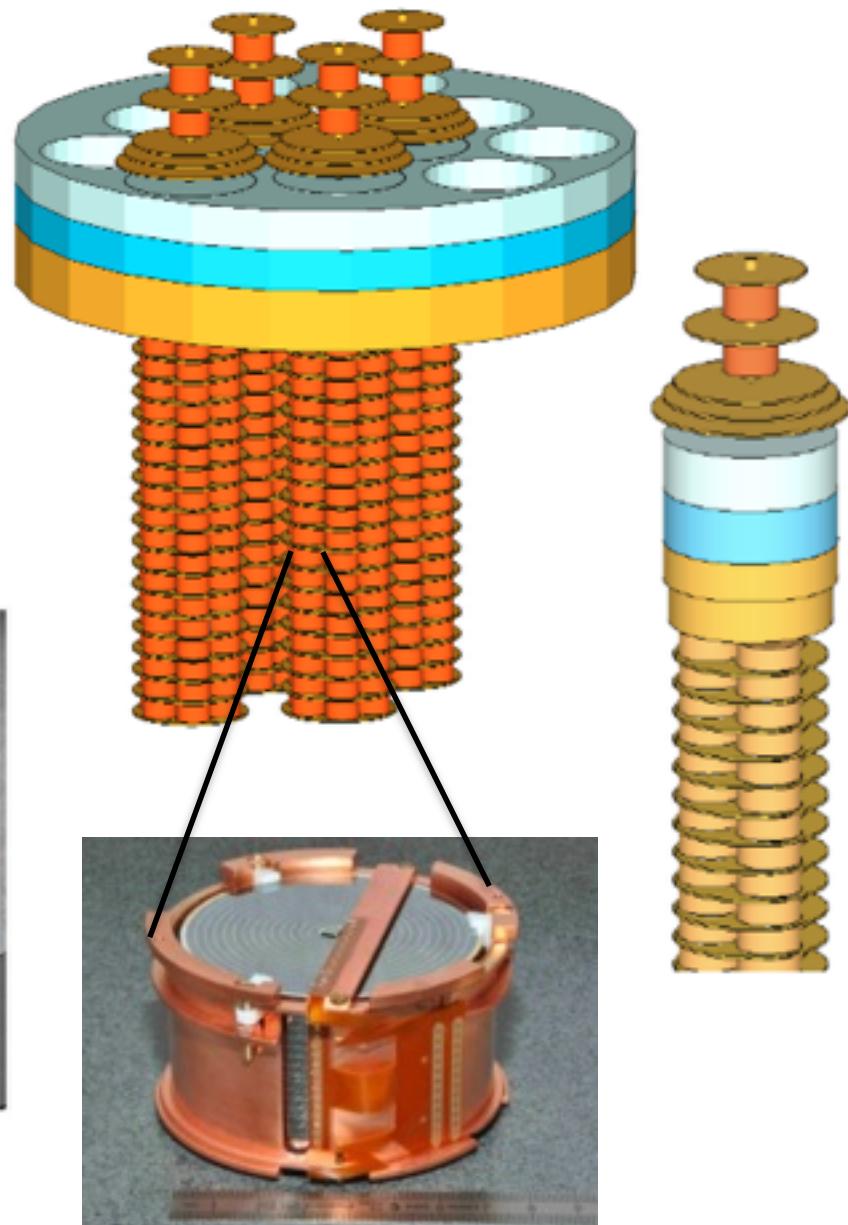
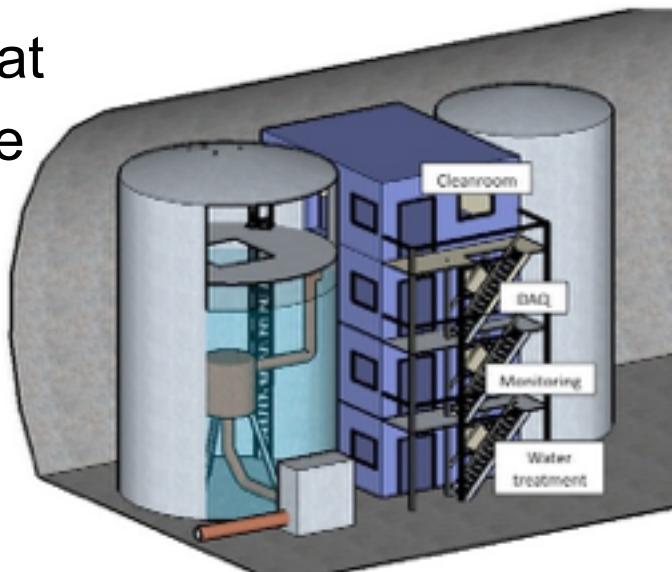
Reach 12000 kg.d (10^{-9} pb)



EURECA: EDELWEISS + CRESST + Others

Conceptual Design of EURECA

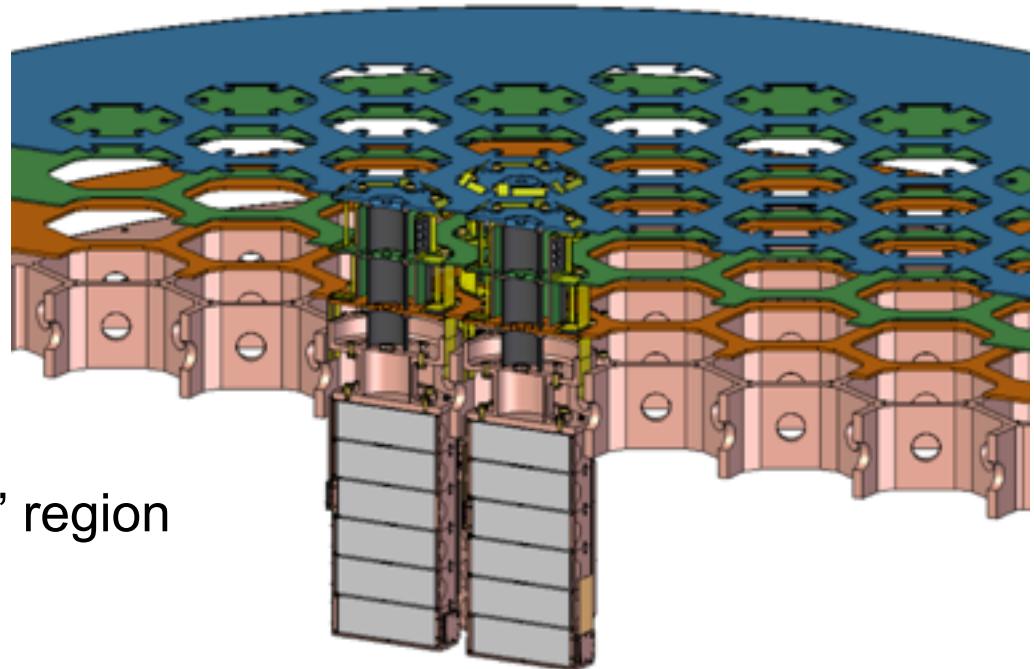
- based on EDW & CRESST technology
- detectors mounted in up to 12 separate towers
 - Baseline design of six 800-g Ge or twelve 300-g CaWO₄ per tower level
 - Option for three 1.6-kg Ge or six 1-kg CaWO₄ per level
- towers in cryostat
- cryostat in active water shield
- 2-phased up to 1 ton



EURECA CDR:
G. Angloher et al., Physics of the Dark Universe 3 (2014) 41–74

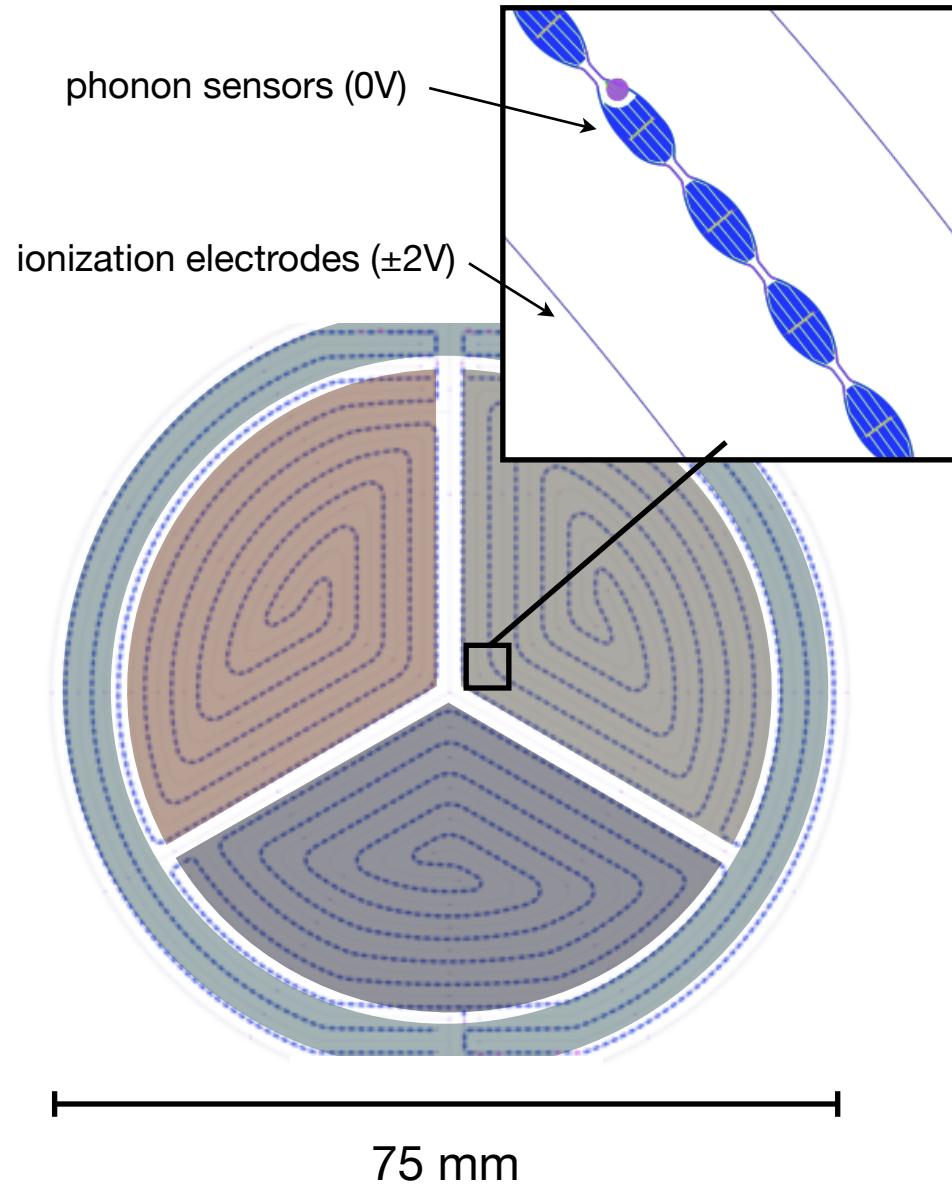
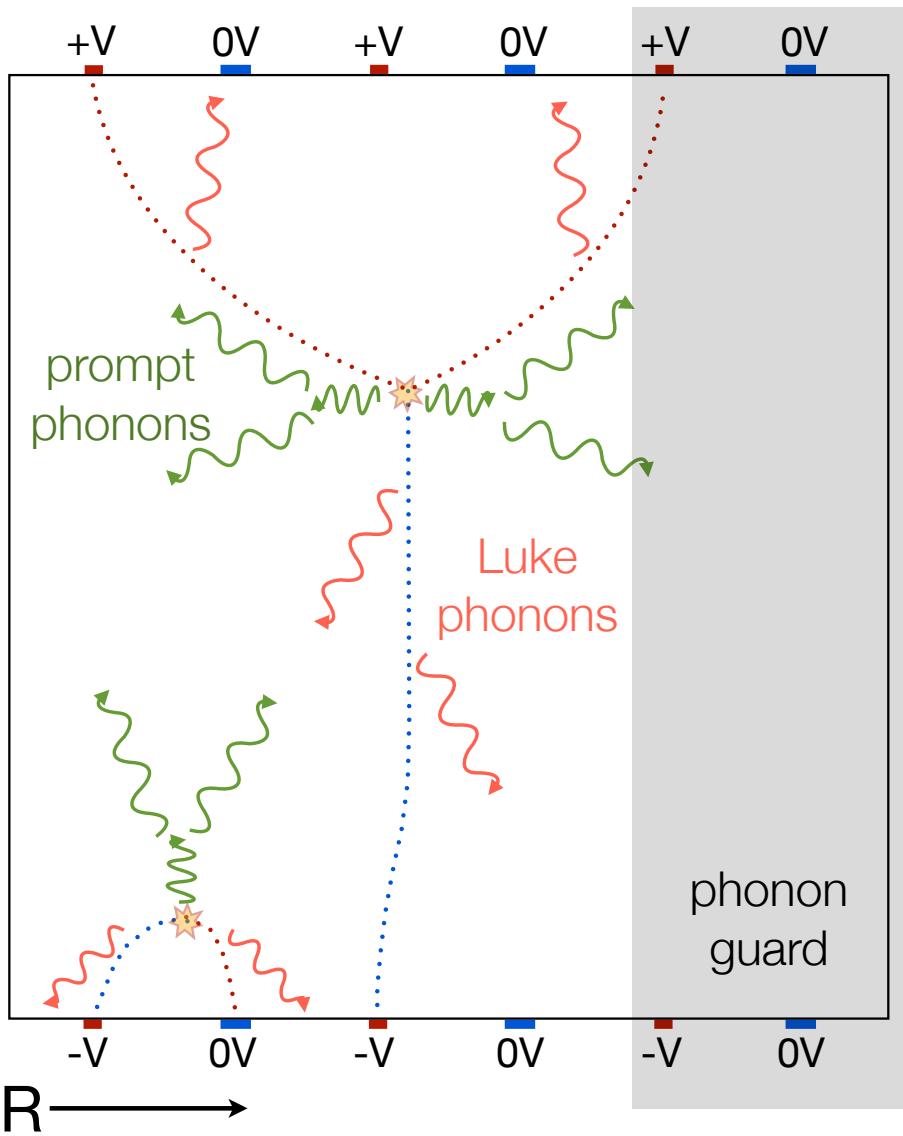
EURECA + SuperCDMS Cooperation

- Builds on earlier collaborative work between EDELWEISS-II & CDMS
 - → Joint publication in Phys. Rev. D 84, 011102(R) (2011)
- Plan to integrate in same cryostat at SNOLAB
 - >100 kg EDW Ge + CaWO₄
 - >100 kg SuperCDMS Ge with common tower design
 - first focus: explore “low-mass WIMP” region
- expected EURECA contribution:
 - cryogenics
 - detector towers & readout
 - optimization of shielding



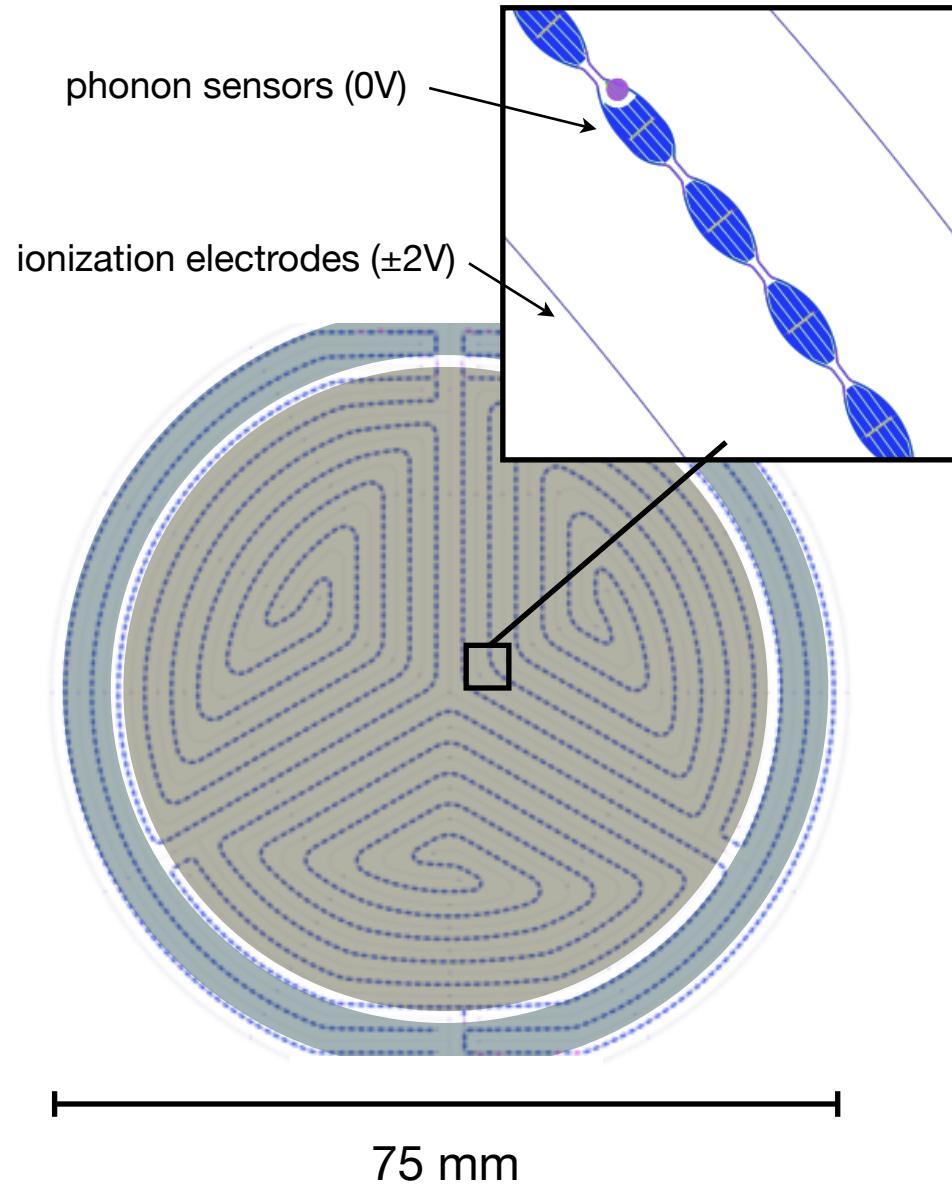
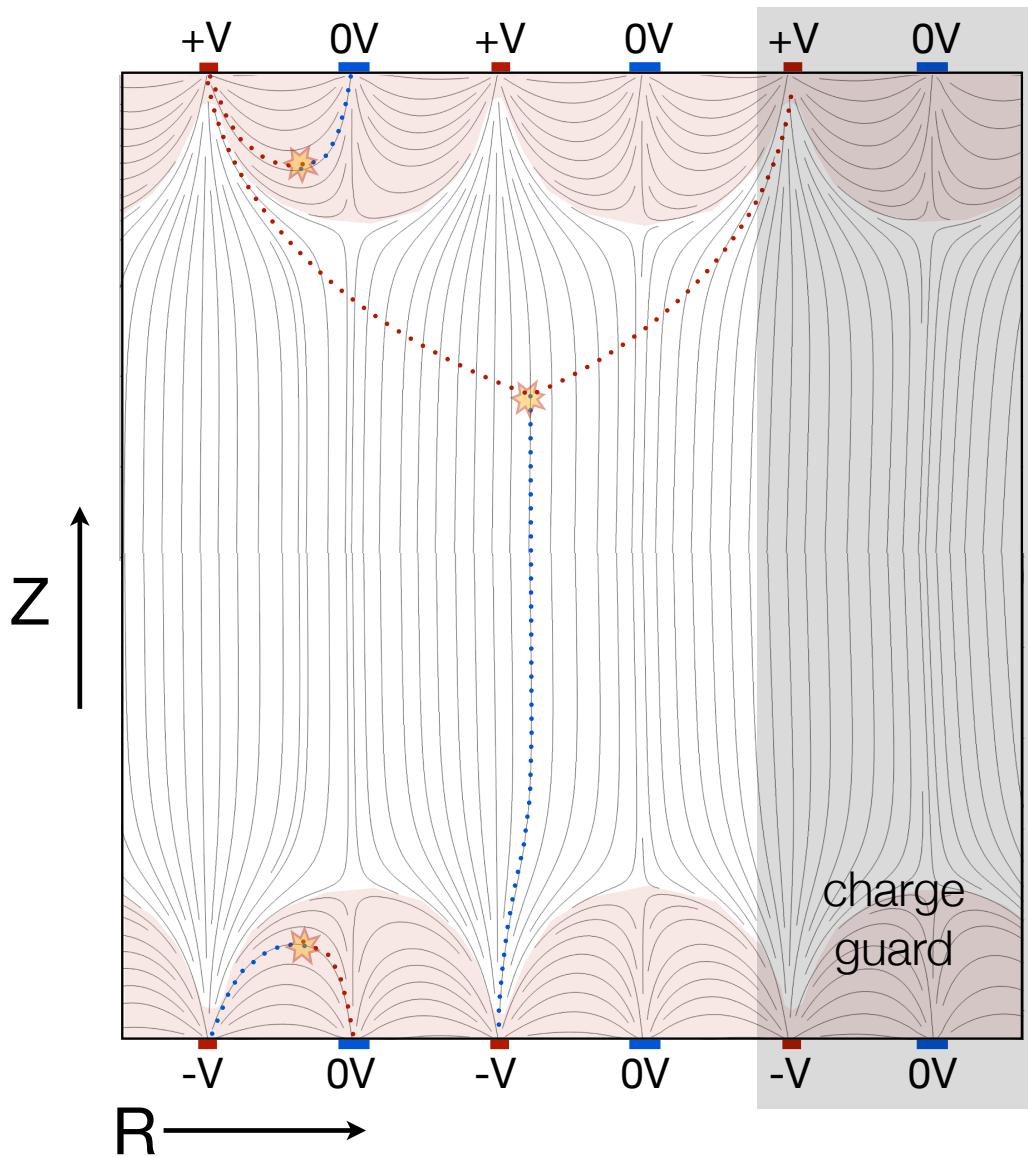
SuperCDMS: Athermal Phonon + Charge

iZIP: interleaved Z-sensitive Ionization and Phonon



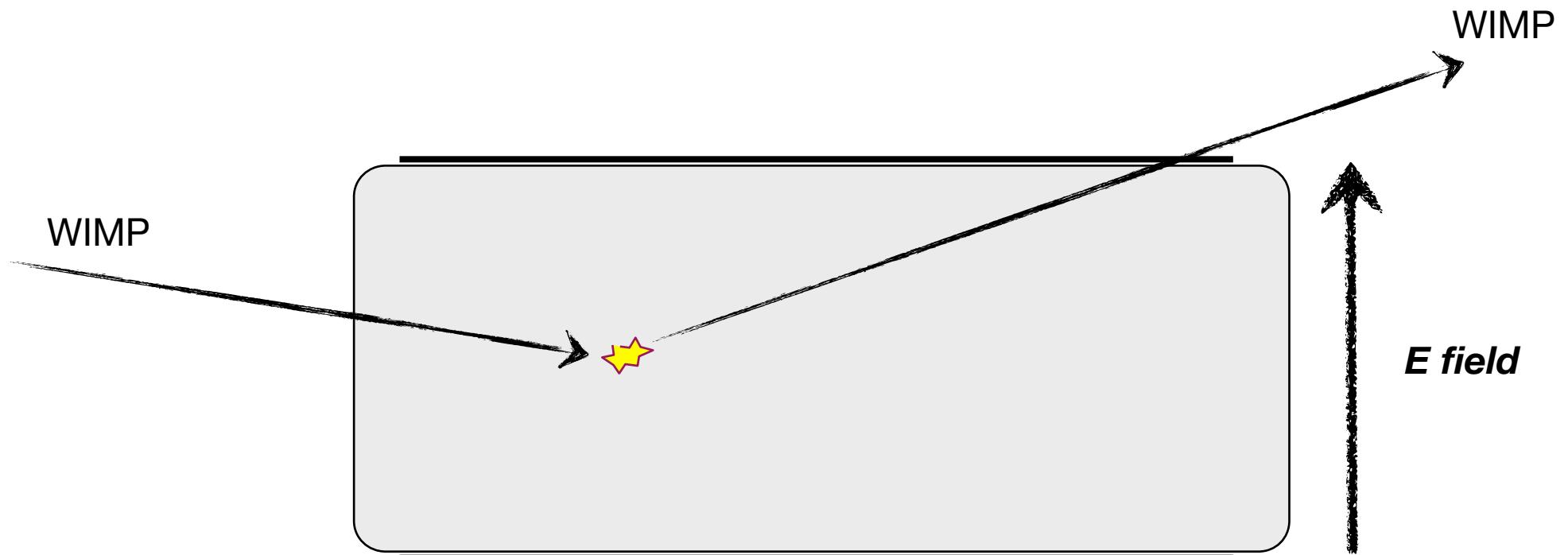
SuperCDMS: Athermal Phonon + Charge

iZIP: interleaved Z-sensitive Ionization and Phonon

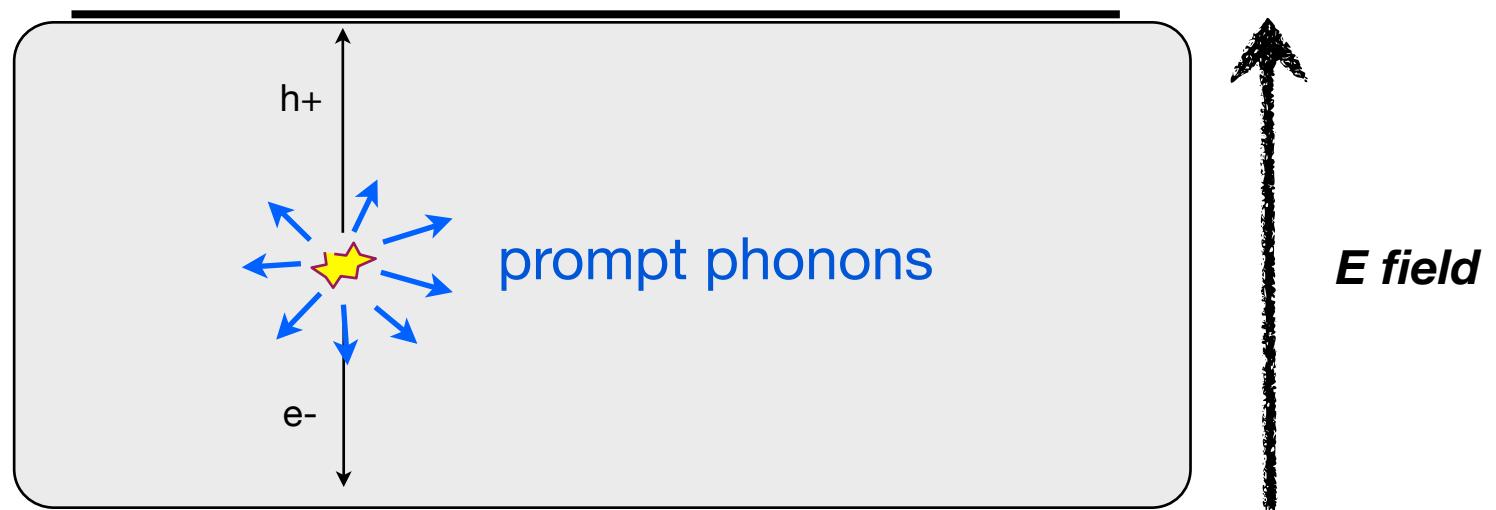


SuperCDMS High-Voltage Operation

CDMSlite: CDMS low ionization threshold experiment



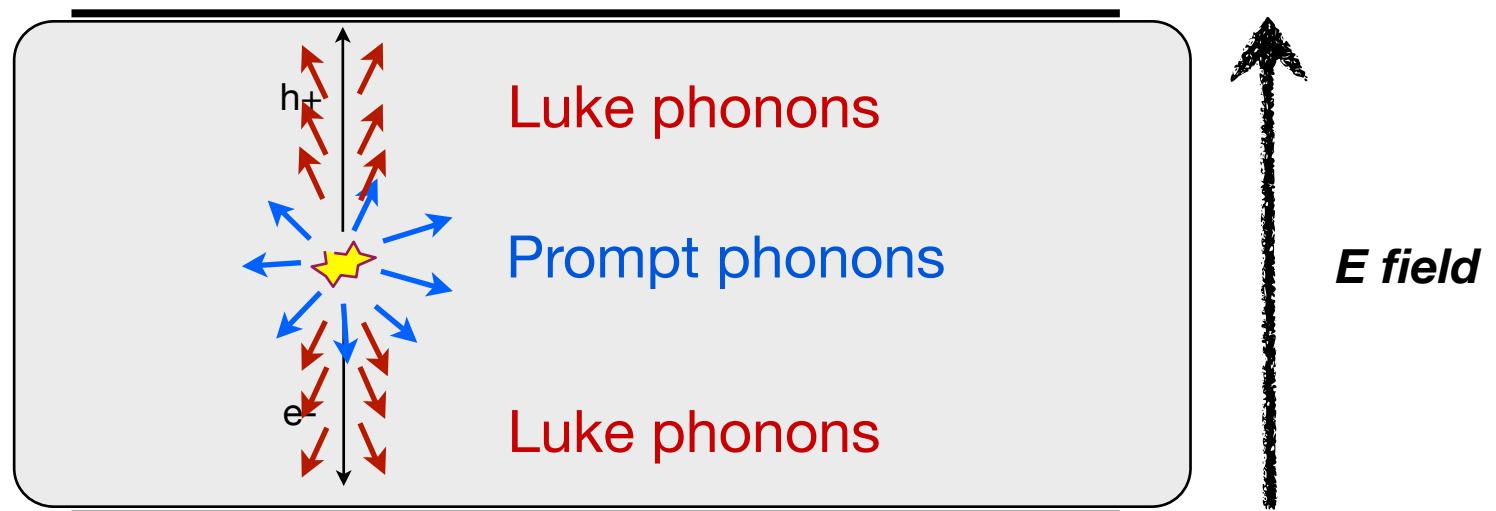
SuperCDMS High-Voltage Operation



SuperCDMS High-Voltage Operation

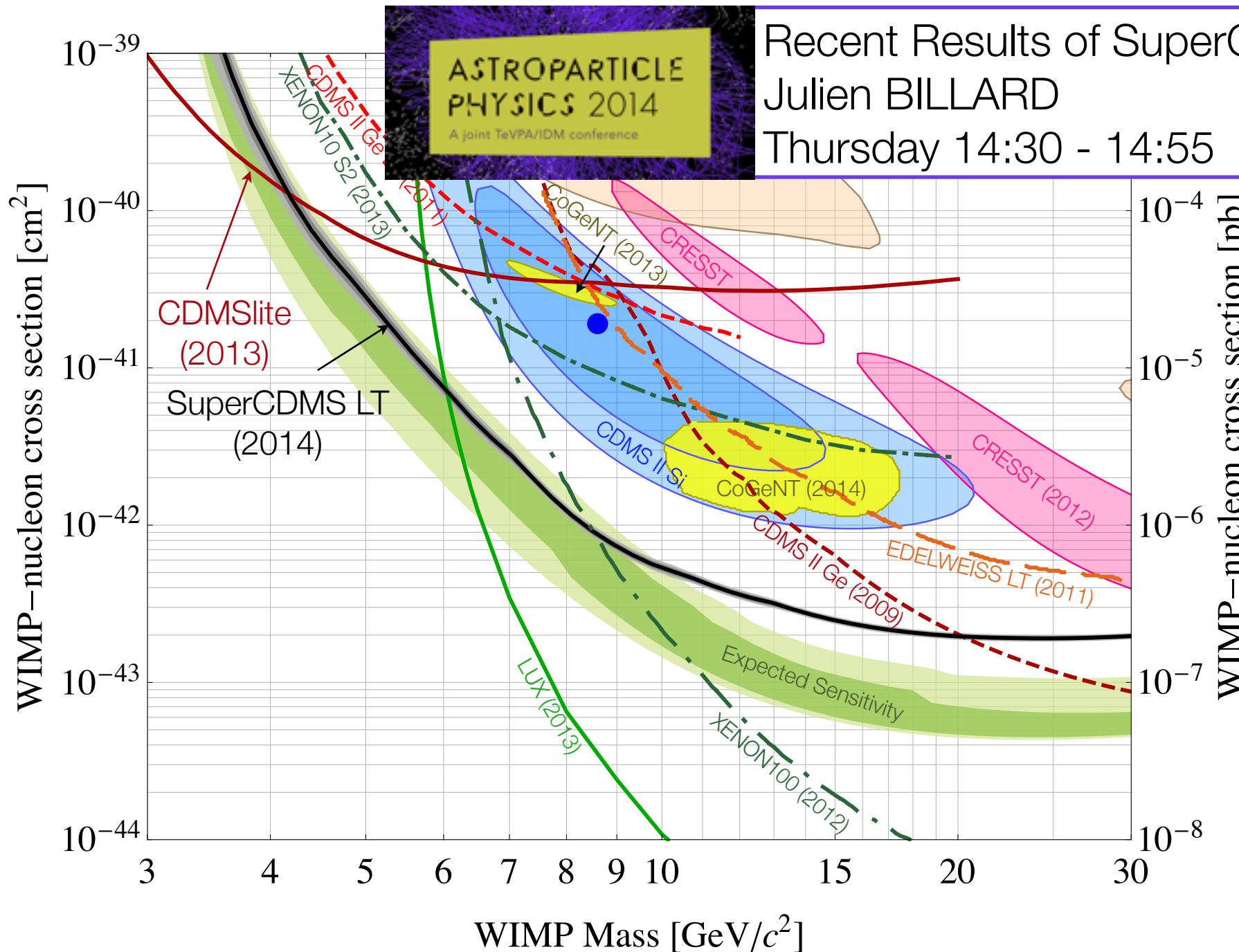
Phonon-based charge amplification

$$\begin{aligned}\text{Phonon energy} &= E_{\text{recoil}} + E_{\text{Luke}} \\ &= E_{\text{recoil}} + n_{\text{eh}} e^- \Delta V\end{aligned}$$



- Phonon resolution can be optimized to $\sigma_p = 50$ eV or better
- Make ΔV large (~ 100 V): use phonons to read out charge

SuperCDMS Soudan Results

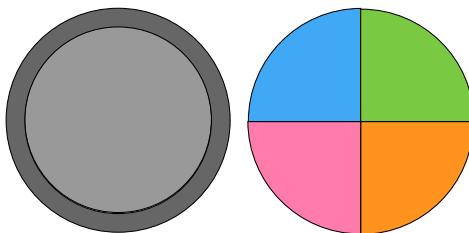


From CDMS II to SuperCDMS

CDMS II

4.6 kg Ge (19 x 240 g)
1.2 kg Si (11 x 106g)
3" Diameter
1 cm Thick

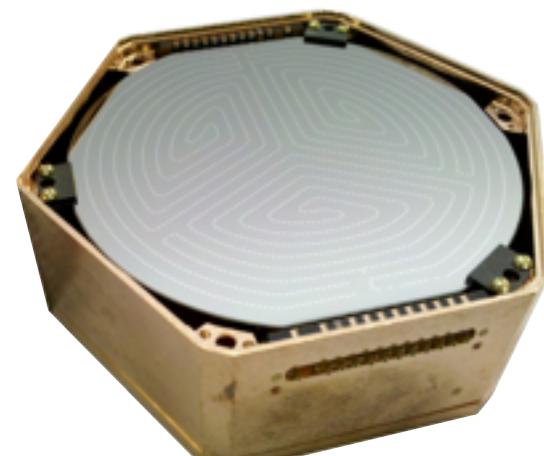
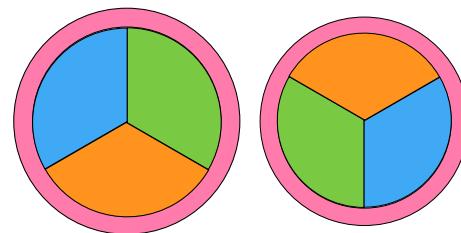
2 charge + 4 phonon



SuperCDMS Soudan

9.0 kg Ge (15 x 600g)
3" Diameter
2.5 cm Thick

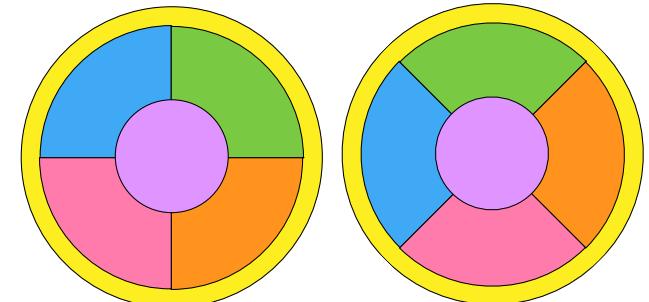
2 charge + 2 charge
4 phonon + 4 phonon



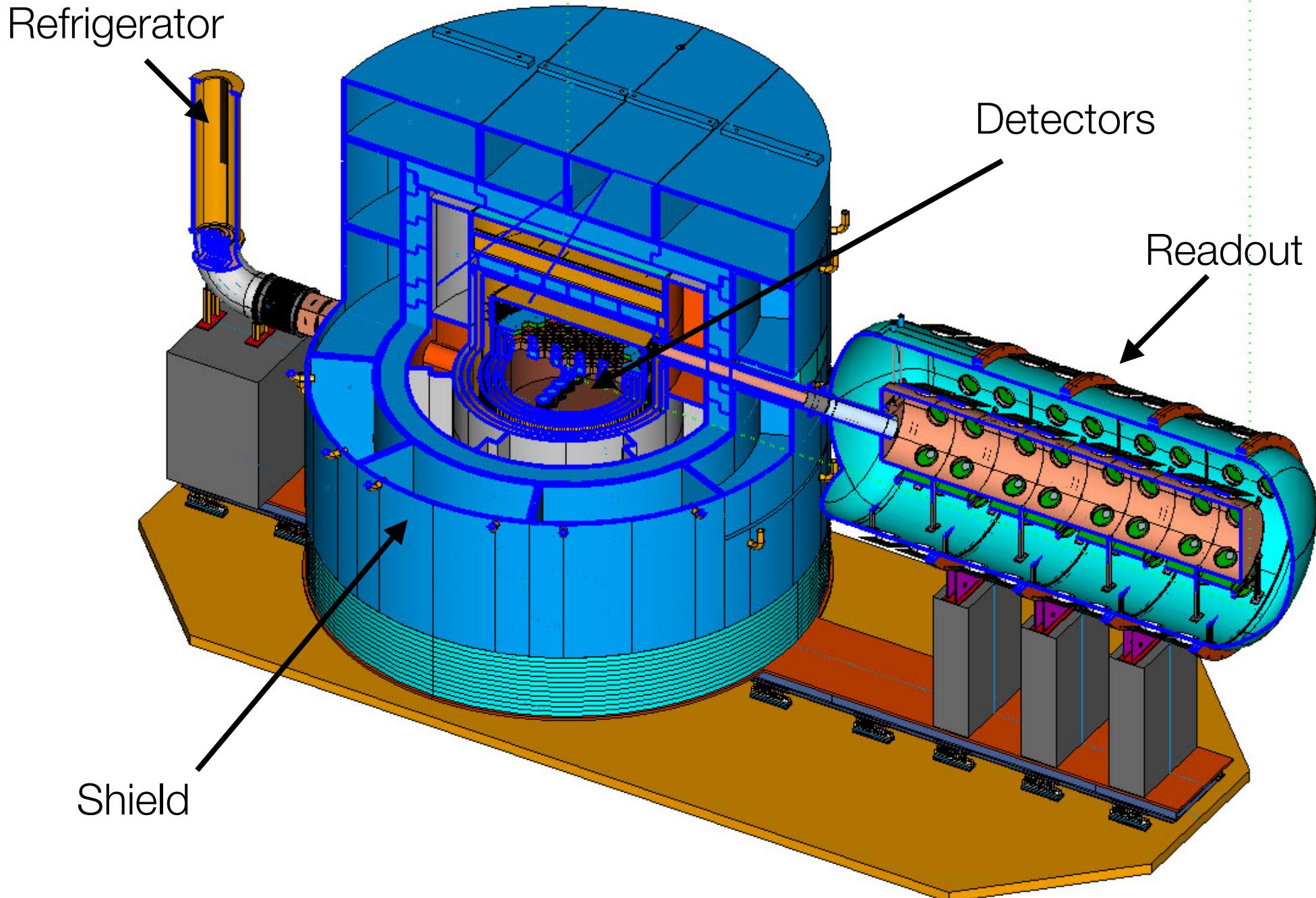
SuperCDMS SNOLAB

98 kg Ge (70 x 1.4 kg)
17 kg Si (20 x 0.6 kg)
4" Diameter
3.3 cm Thick

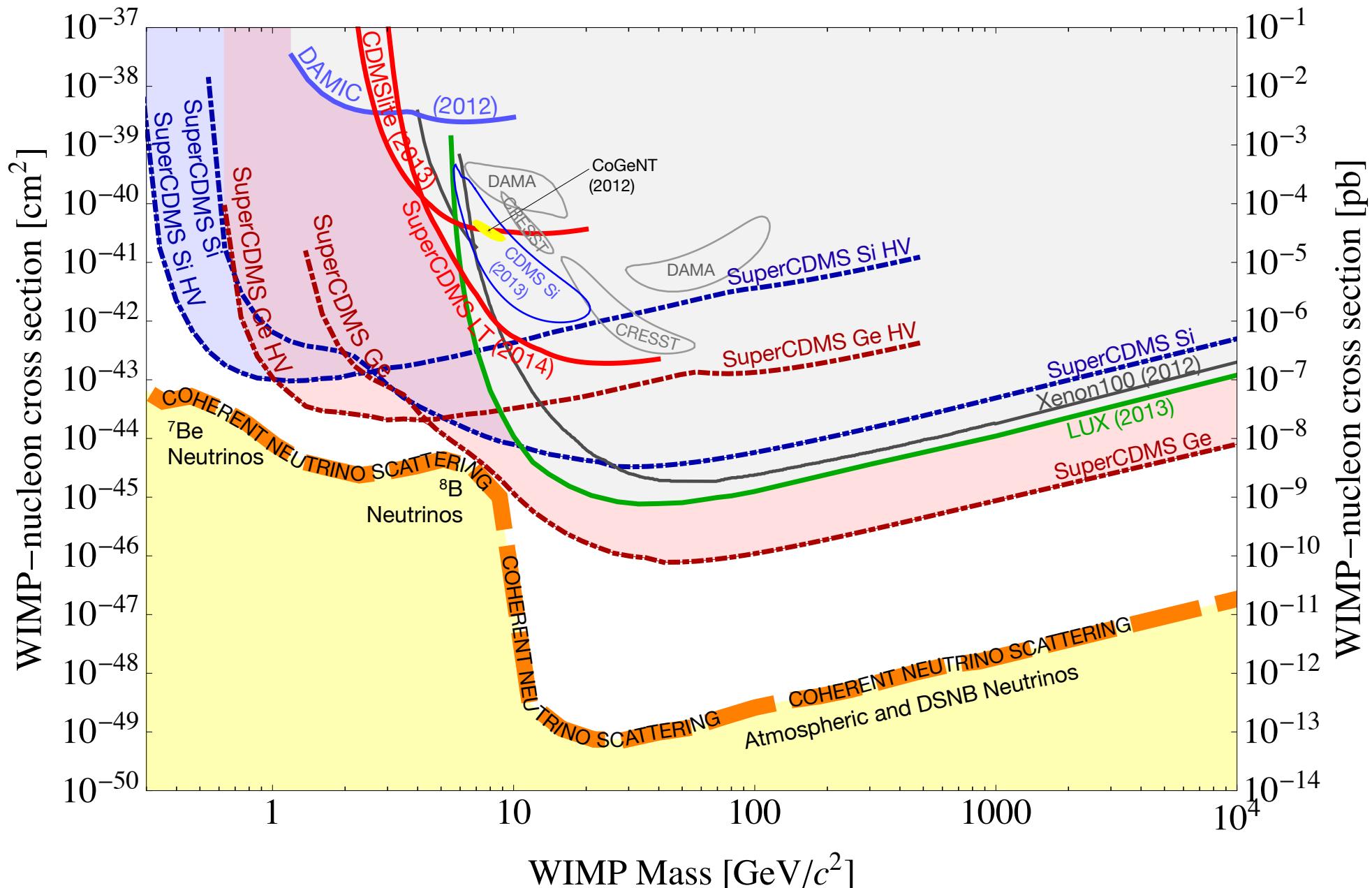
2 charge + 2 charge
6 phonon + 6 phonon



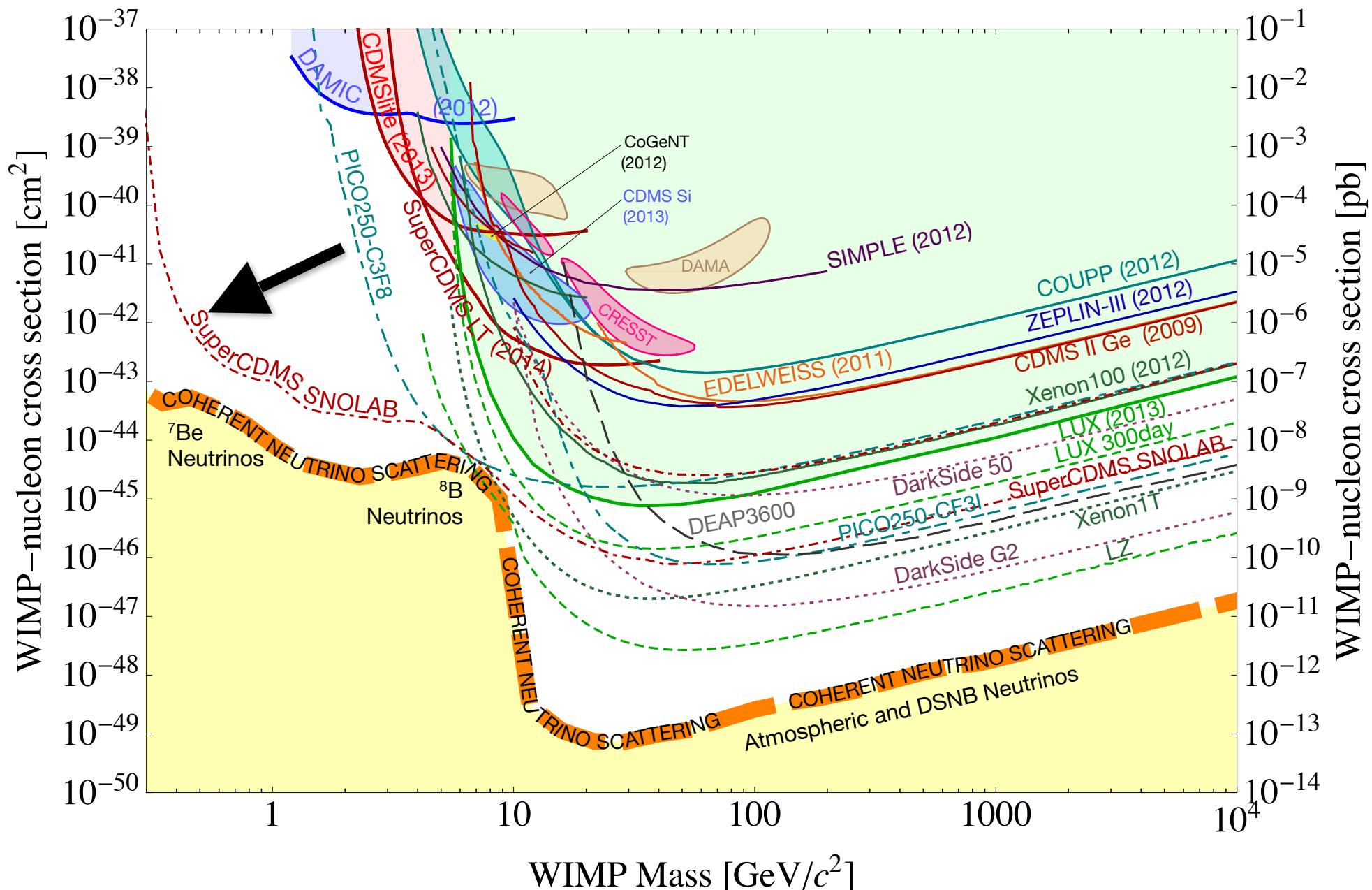
SuperCDMS SNOLAB @ the Ladder Lab



G2: SuperCDMS SNOLAB



G2: The entire community



Conclusions

- Well motivated models of dark matter exist at a wide range of masses... we need a broad search!
- To extract all the information available through direct detection of dark matter, multiple target materials are essential
- Cryogenic detectors with phonon readout enable low-thresholds and circumvent quenching factor issues at the lowest recoils
- The next generation of experiments will begin to map out the neutrino floor by detecting 8B solar neutrinos
- G2 cryogenic detectors will have unprecedented reach for dark matter masses of a few GeV, and will be an important cross check of potential signals in the high mass range