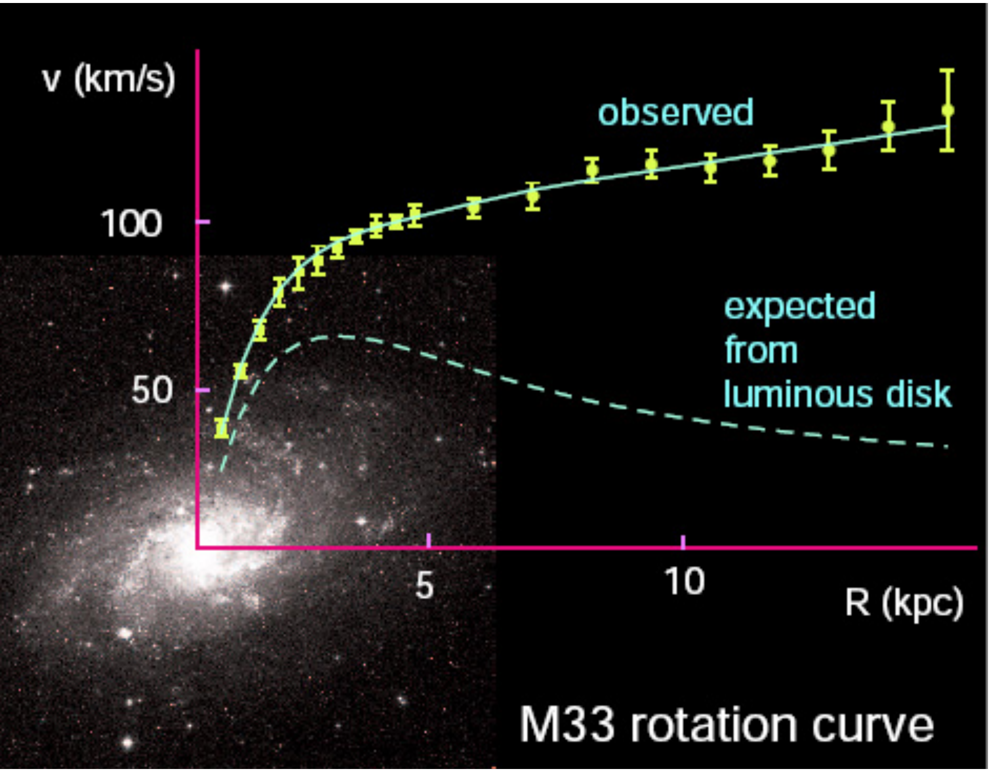
Dark Matter:
Theory and Detector Design Drivers

Matt Pyle
University of California
Berkeley

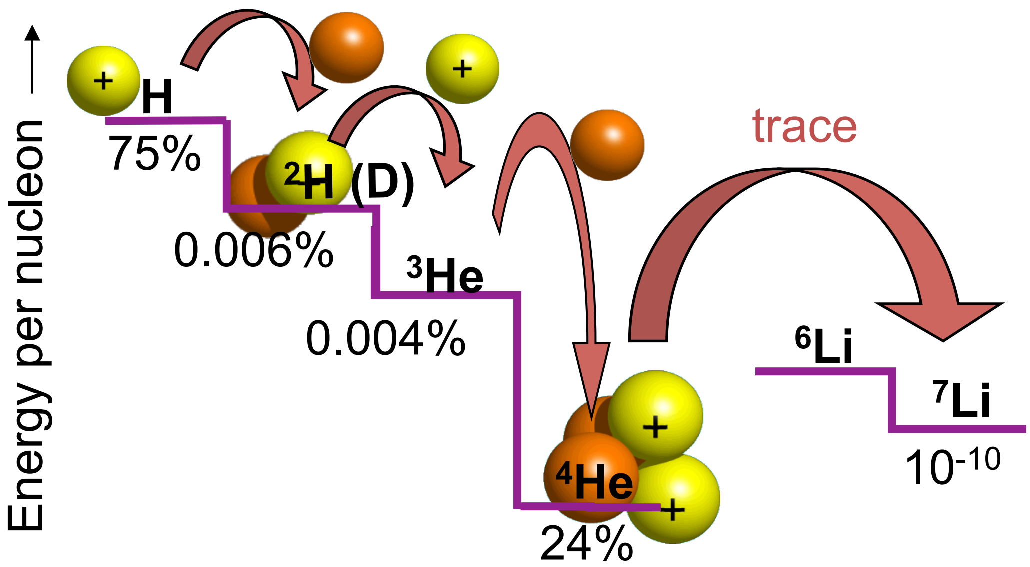
Oct 5 2015

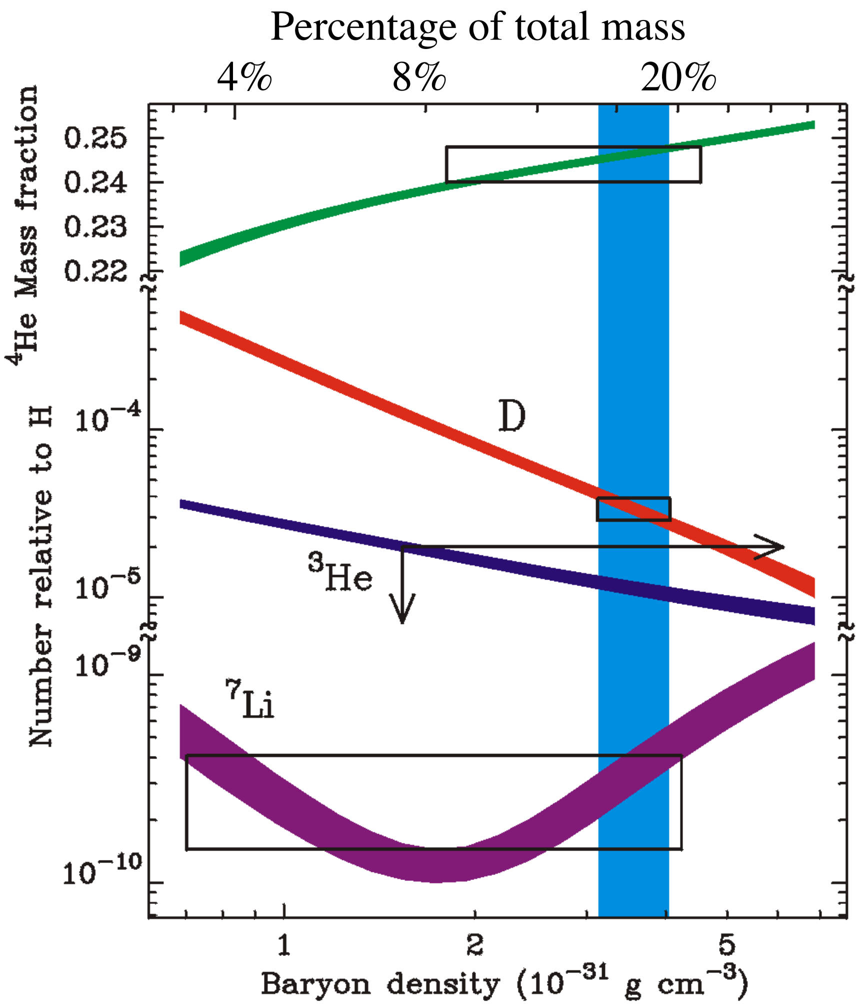
Dark Matter



Most of the mass in the universe is dark particles

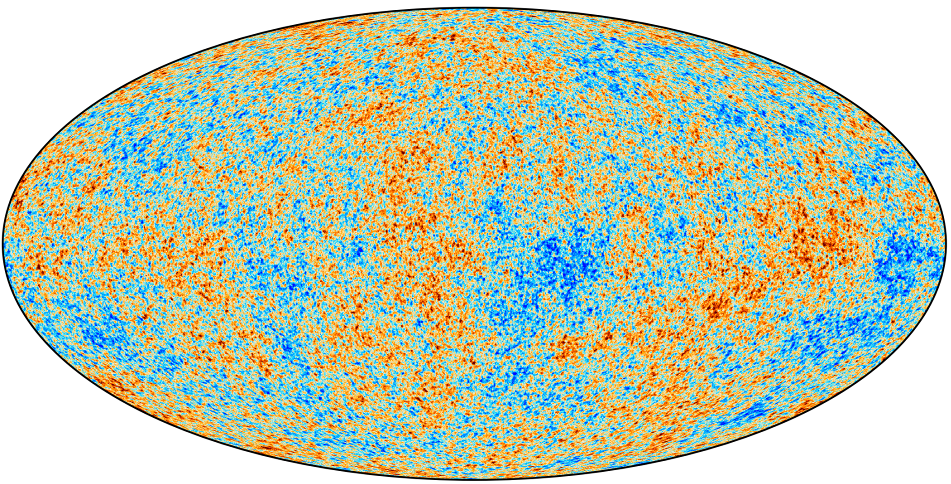
Dark Matter: Big Bang Nucleosynthesis



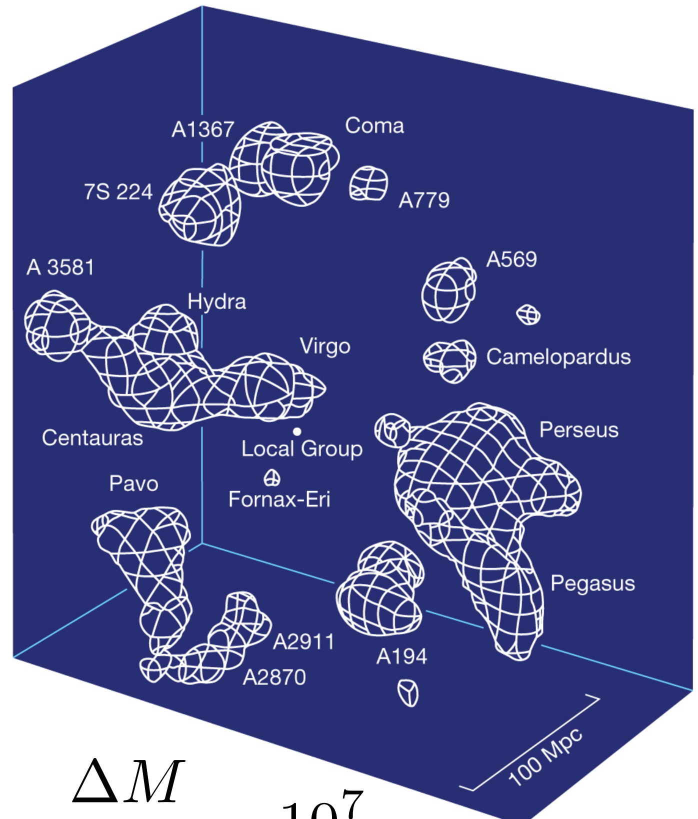


Dark Matter is non-Baryonic

Dark Matter: Structure Formation



$$\frac{\Delta T}{T} \sim 10^{-5}$$



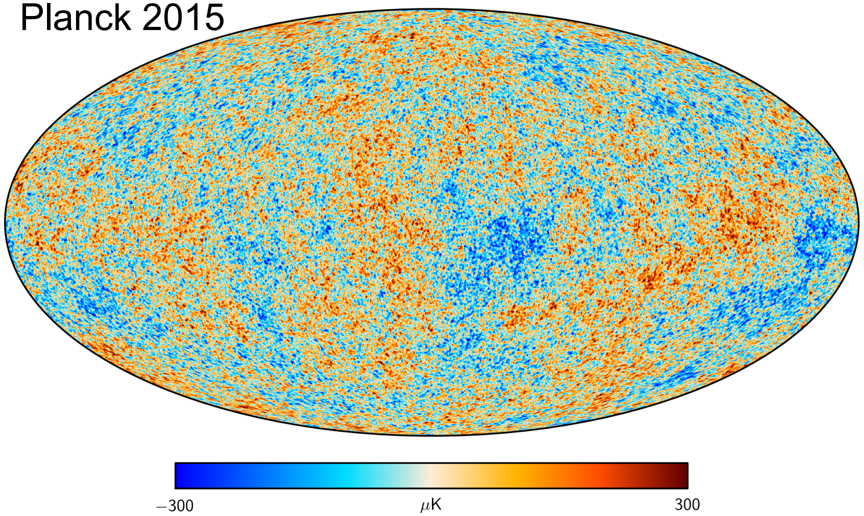
$$\frac{\Delta M}{M} \sim 10^{7}$$

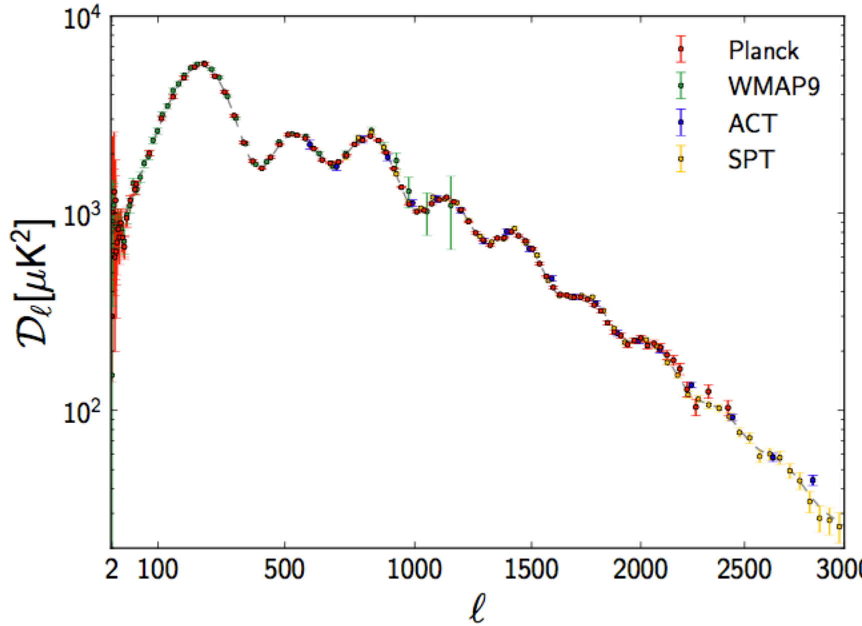
Dark Matter is Cold

Dark Matter: CMB

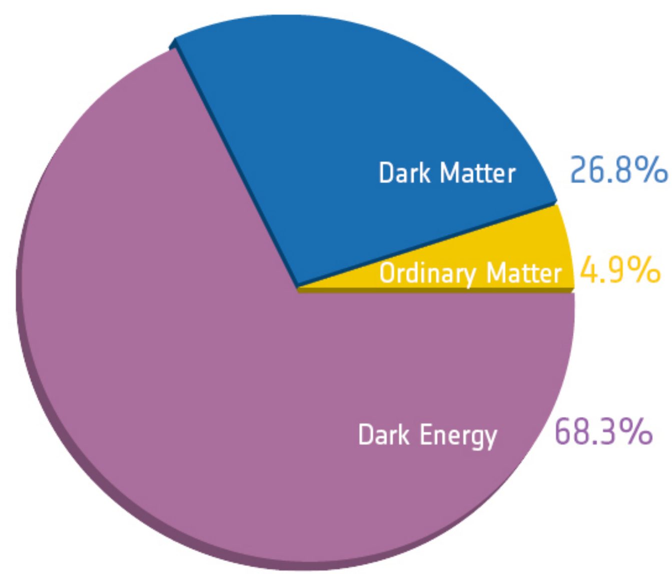
"Precision Cosmology"

Planck 2015



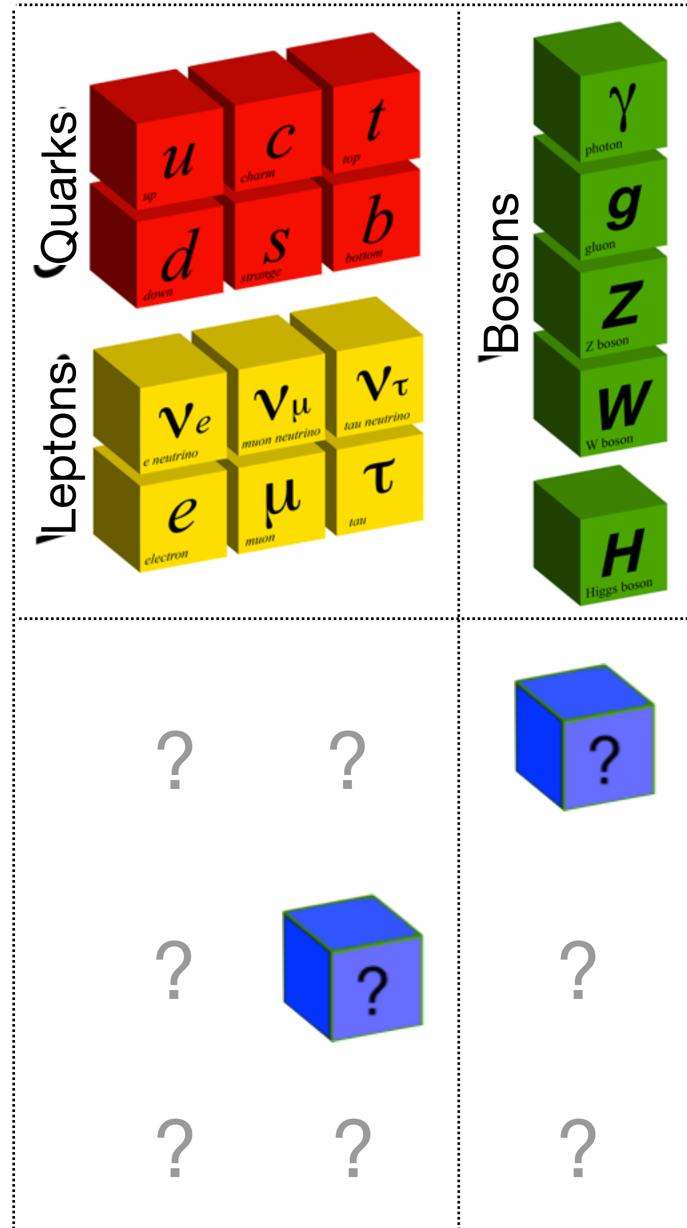


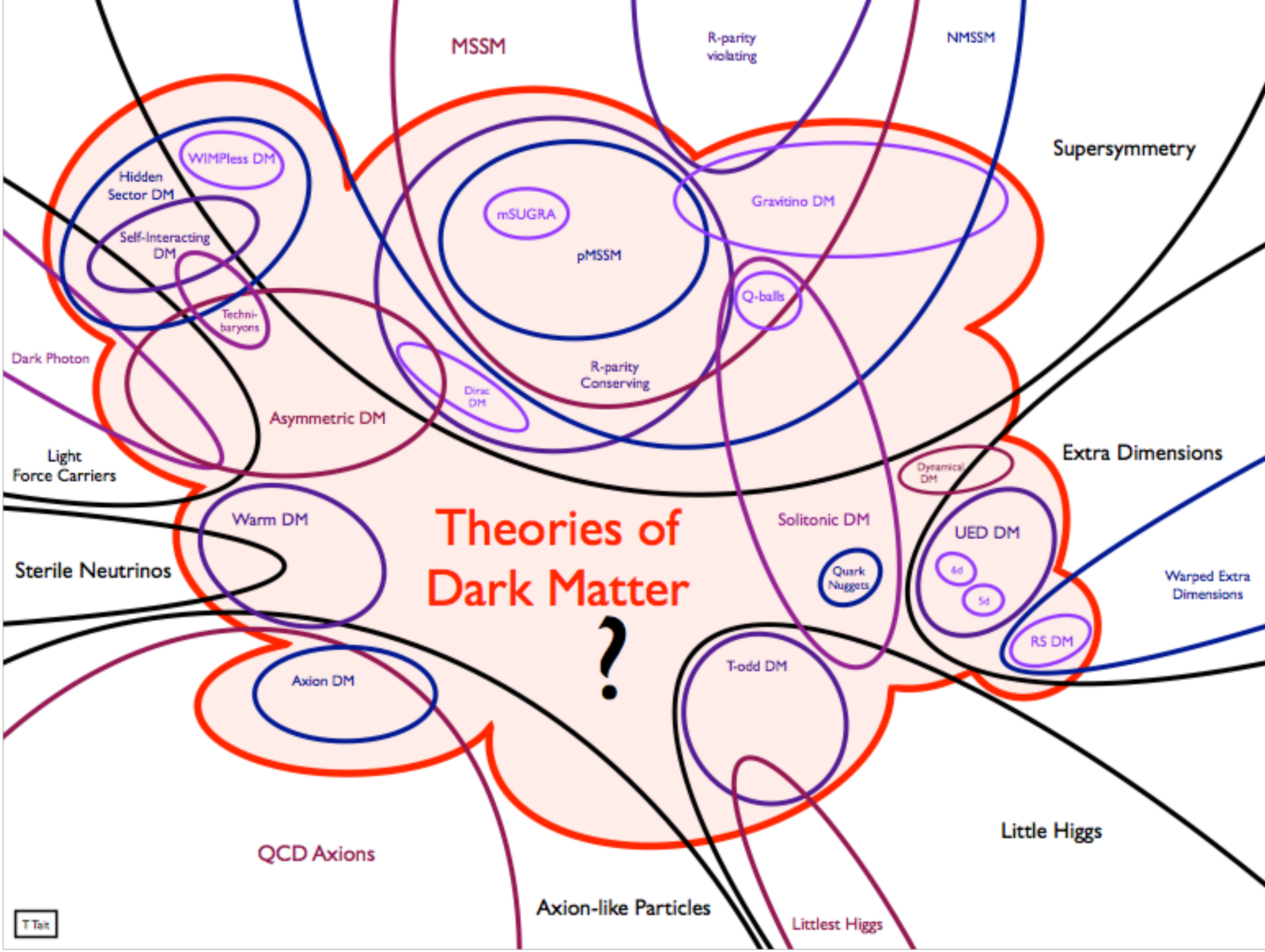
Complete Confirmation: Dark Matter is cold and non-Baryonic



Dark Matter & Particle Physics

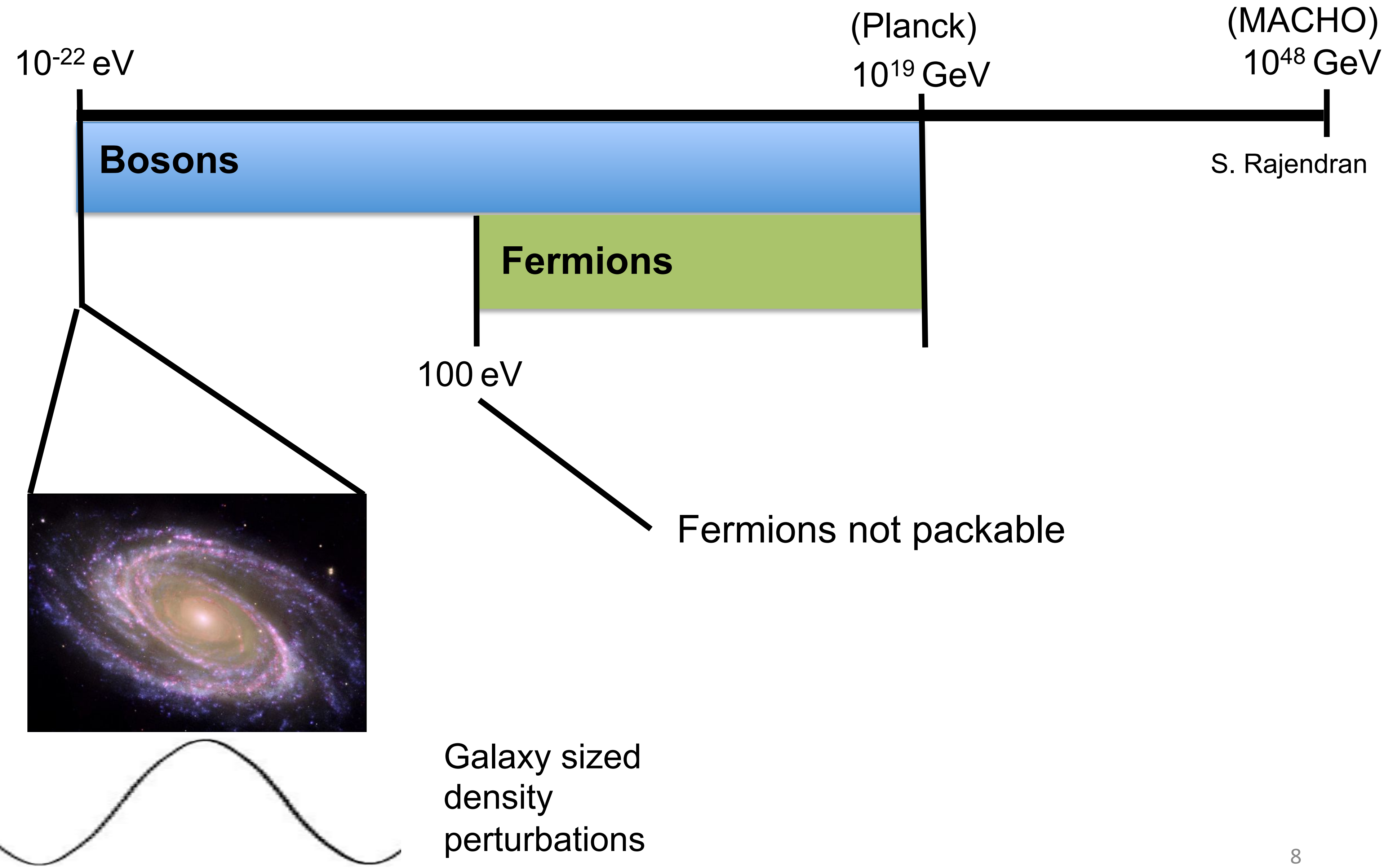
- How does it fit into the visible world that we know?
- What are it's properties?
  - Mass ?
  - Spin ?
  - Dipole Moment?
- How does it interact?
- What does it tell us about how the universe works?



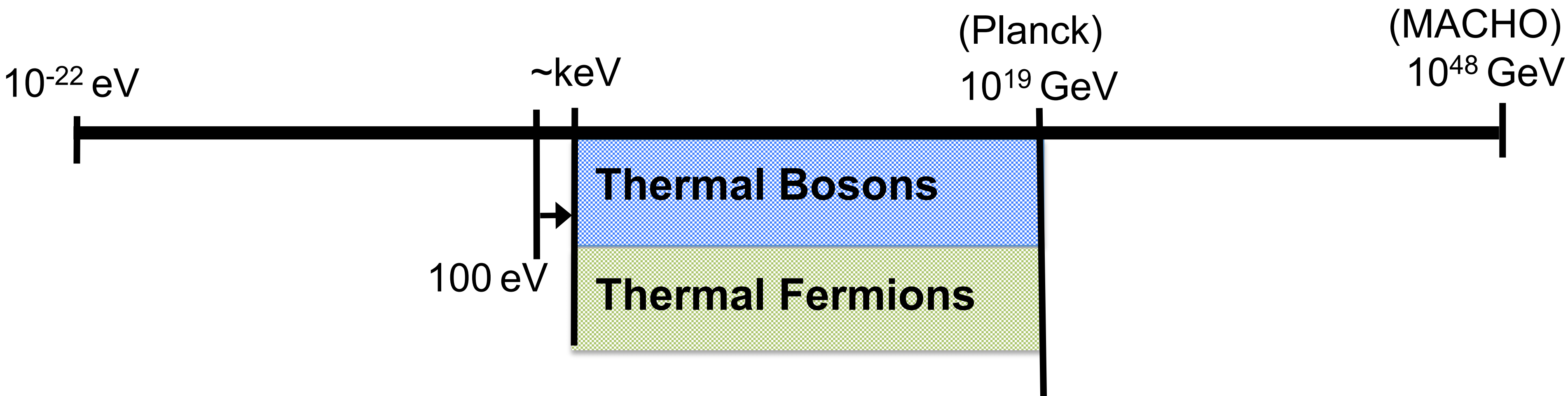


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dark Photon
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
6d
5d
Quark Nuggets
Sterile Neutrinos
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

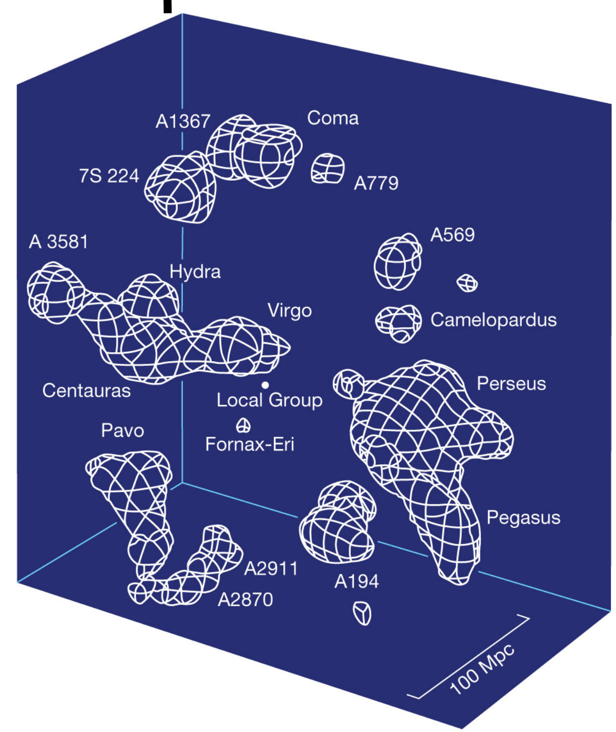
Dark Matter: Type(Mass)



Dark Matter: Production & Coldness



- DM particles thermally produced in the early hot universe
- Relativistic particles don't clump



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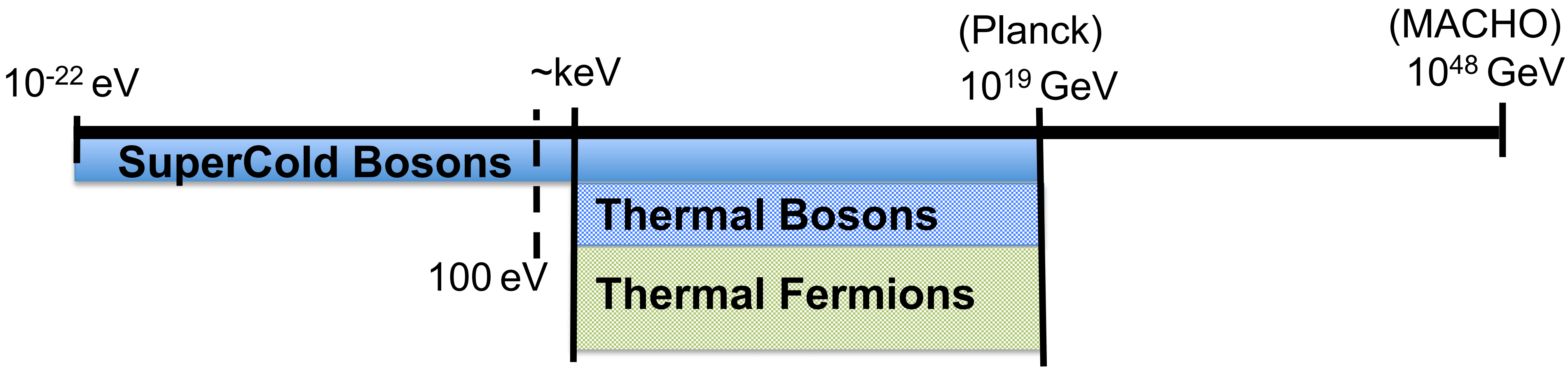
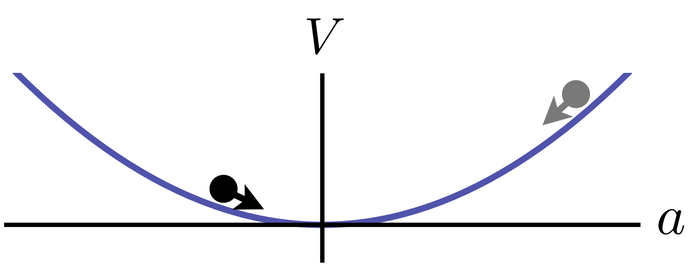
Dark Matter: Production & Coldness

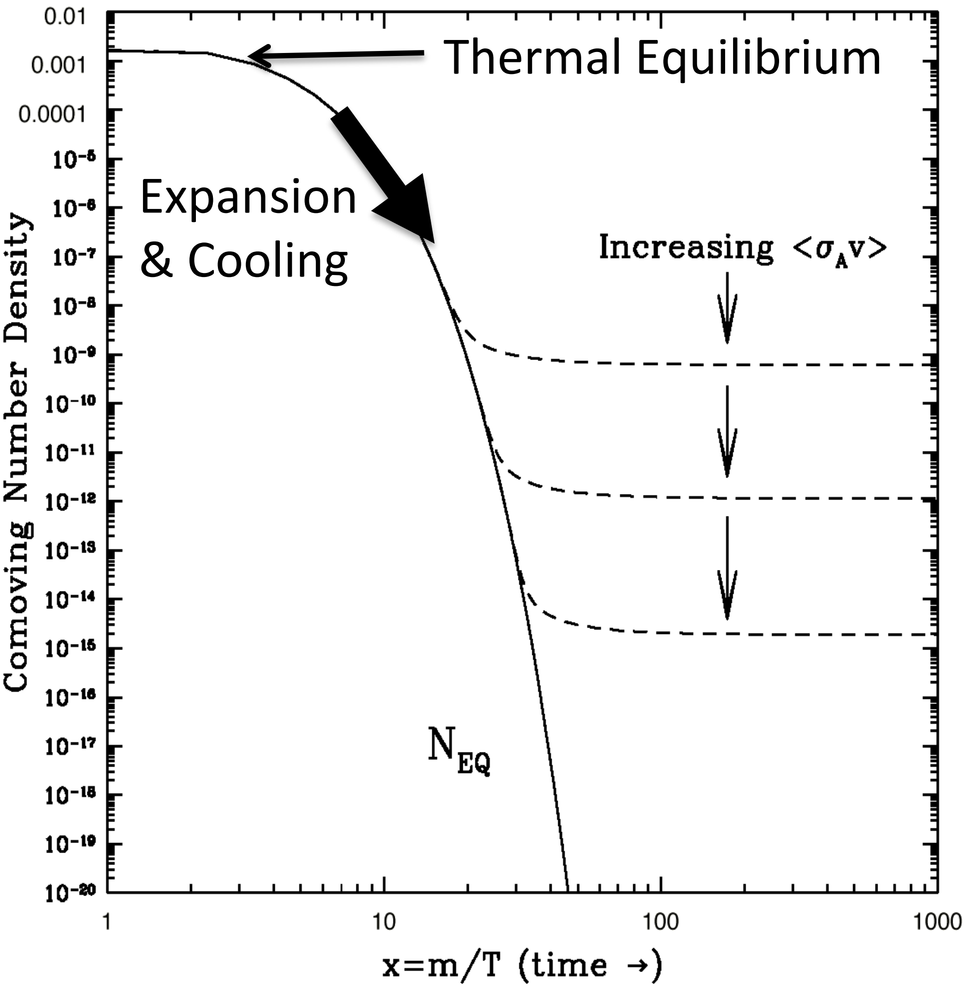


Misalignment Mechanism



- Misalignment Mechanism
  - Initial value of field not near the minimum
  - Bosons are super cold
- Production during Inflation (Vector bosons only)
  - Graham, Mardon, Rajendran: 1504.02102

WIMP Miracle: Thermal Freeze Out +Supersymmetry

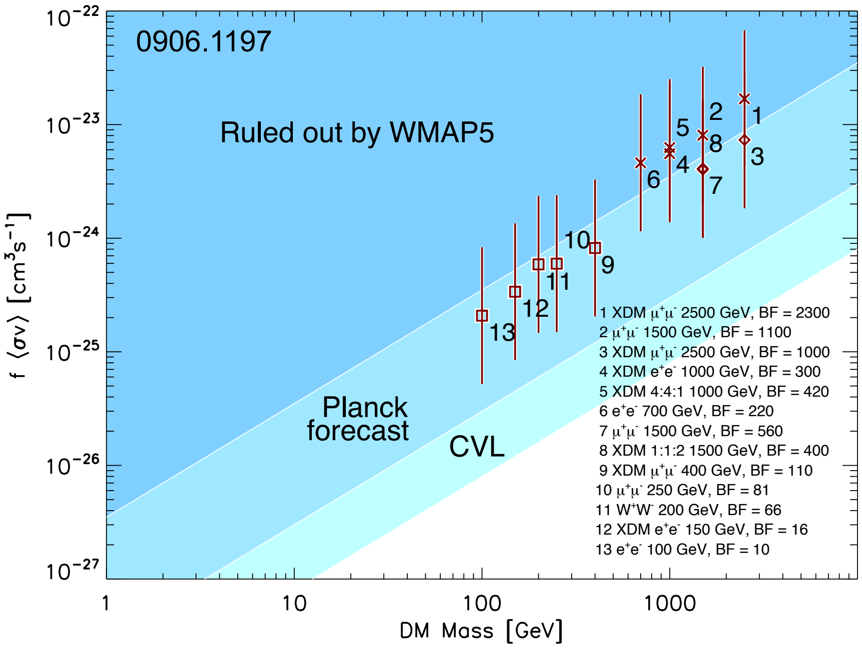


- Relic DM density suggest weak scale cross sections
- New physics (and particles) at the weak scale could solve the hierarchy problem

WIMPs: CMB Lower Bound

$$\frac{dE}{dtdV} \propto M_{DM} n_{DM}^2 < \sigma v >$$

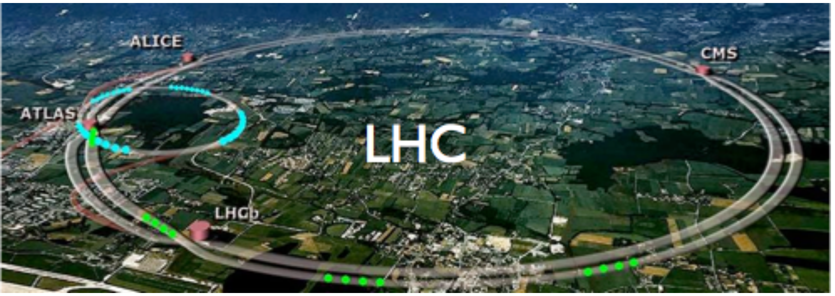
$$\propto \rho_{DM}^2 \frac{< \sigma v >}{M_{DM}}$$

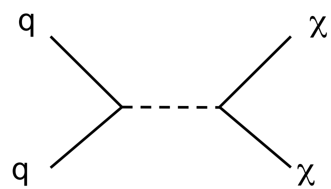


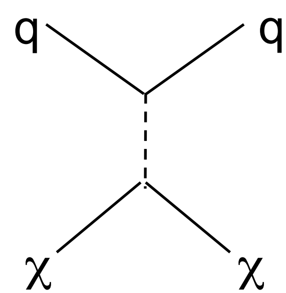
- Energy Injection During Recombination
  - delays photon decoupling
- Energy Injection after recombination increases optical depth
  - more ionized particles = more scatter
- Slayter et al, 0906.1197

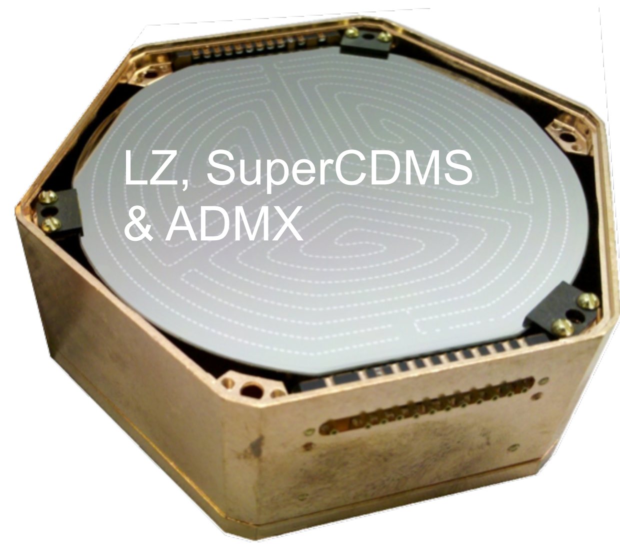
$M_{WIMP} > \sim 10 GeV$

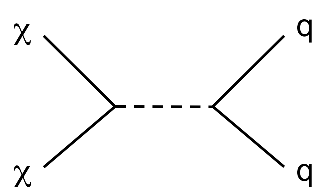
Dark Matter Search Techniques



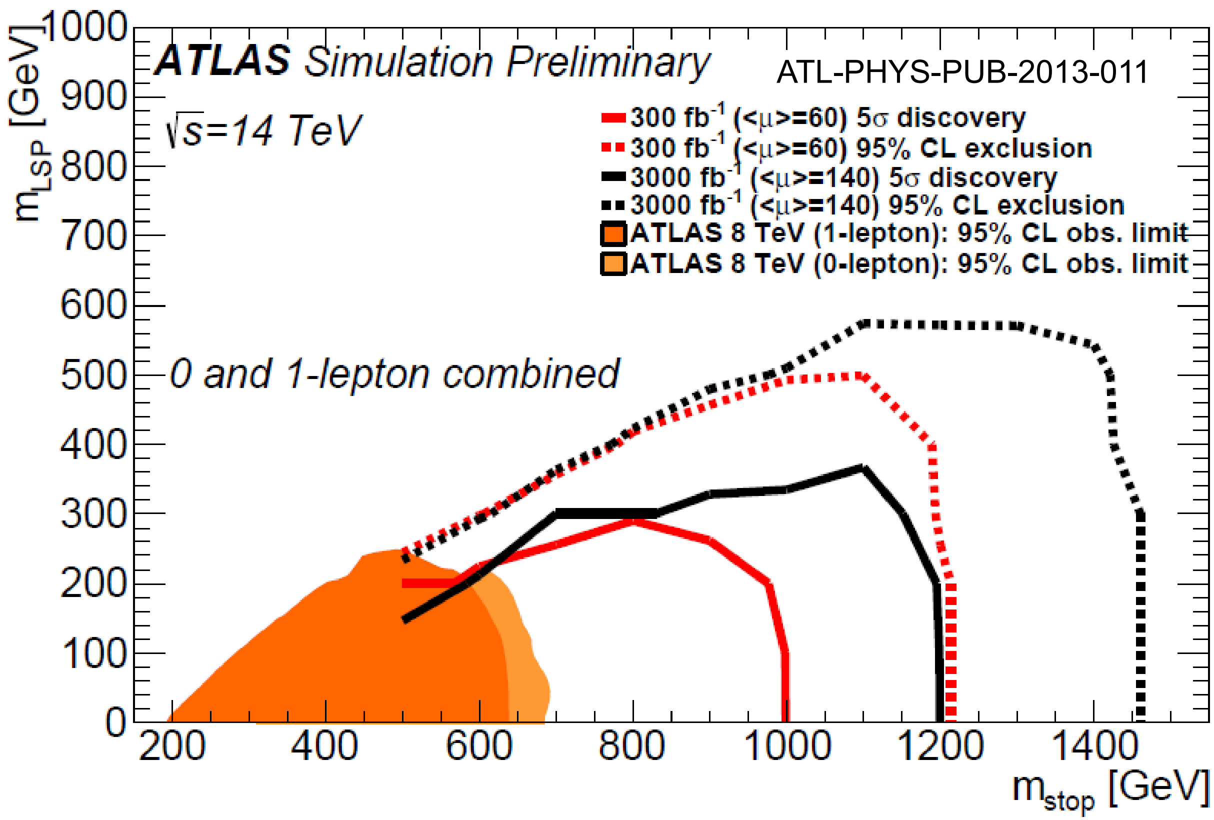






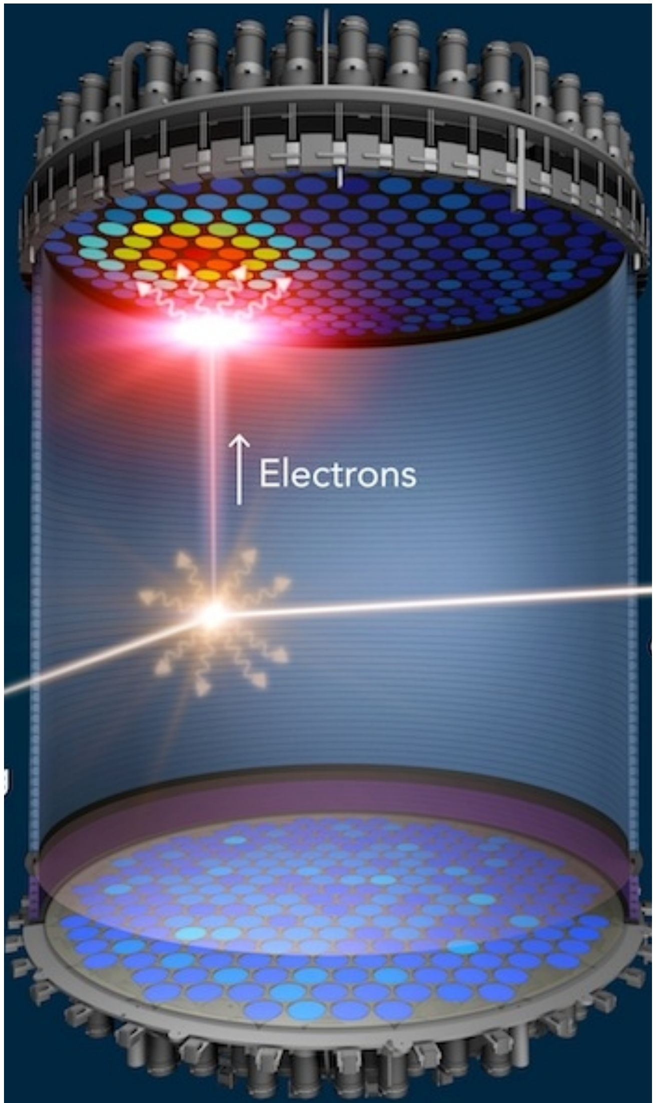


WIMPs: Future @ Accelerators



- LHC Run 2 ongoing!
- 7 TeV -> 13TeV
- Large fraction of the remaining SuperSymmetry will be probed

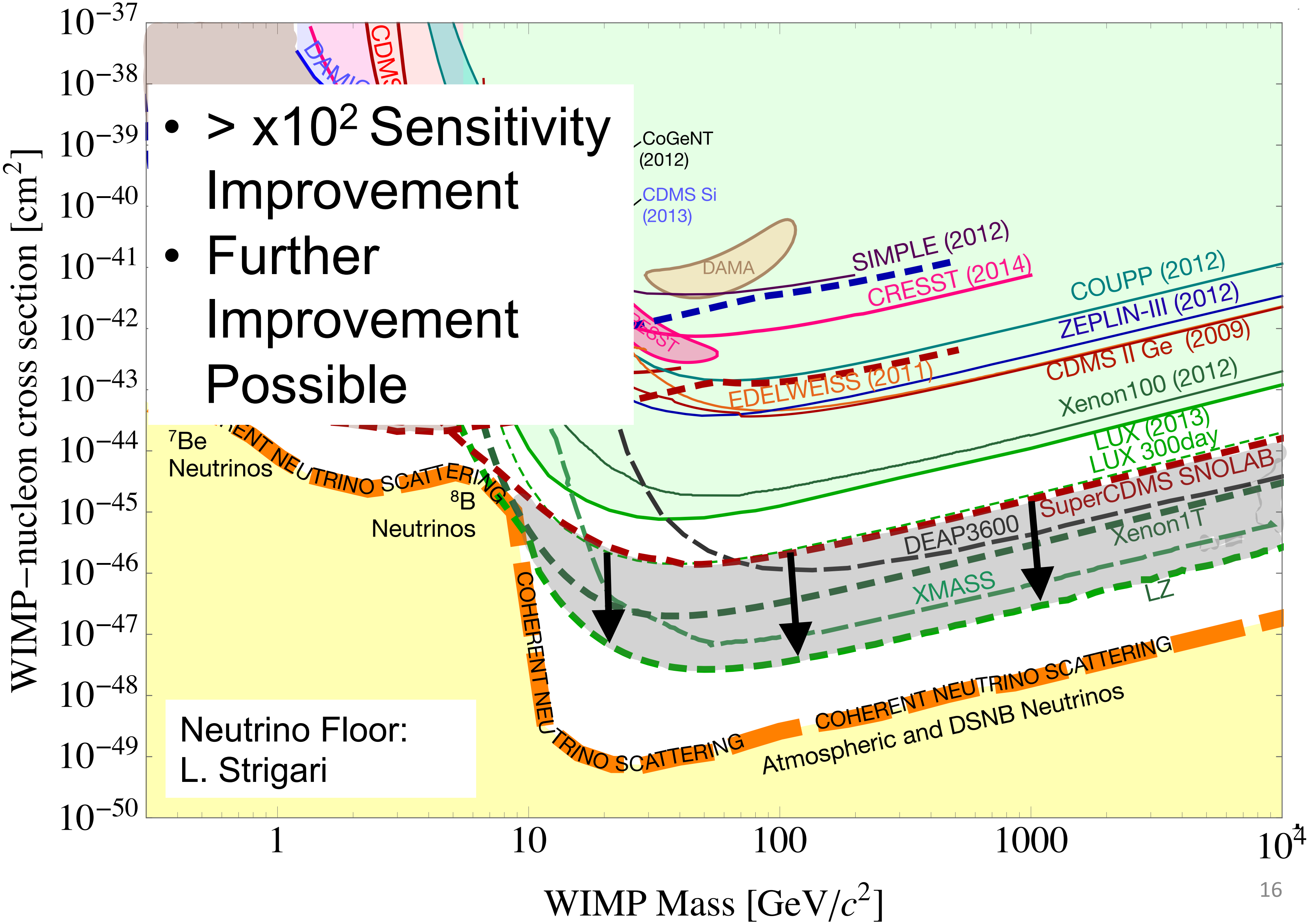
WIMP Direct Detection Detector: 2 Phase Noble TPC



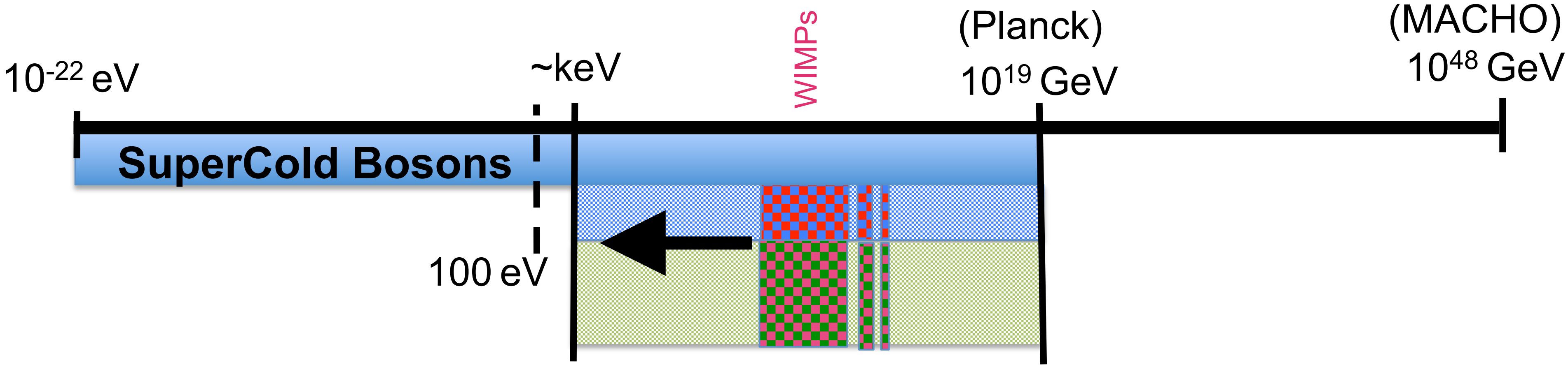
- G2: LZ and XENON 1 Ton
- Xe / Ar / Ne / He
- Measures both Ionization & Scintillation
- Design Drivers:
  - Minimize Backgrounds
    - intrinsically clean
    - self shielding
    - Electron Recoil / Nuclear Recoil Discrimination
  - Large Exposure
    - Big Active Volume
  - Talks:
    - T. Shutt
    - B. Jones
    - M. Leyton
    - Y. Li

WIMP Direct Detection: Future

- > x10[2] Sensitivity Improvement
- Further Improvement Possible

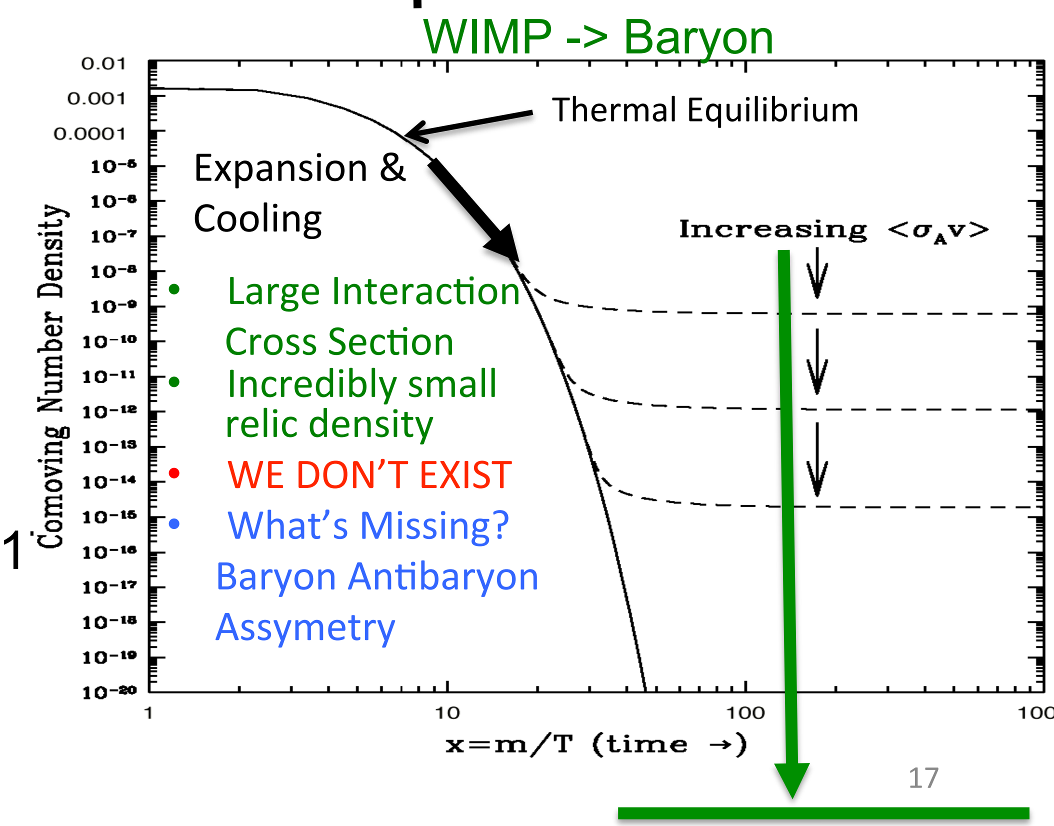


Dark Matter: Explore Lower Masses?



Thermal Production Mechanisms

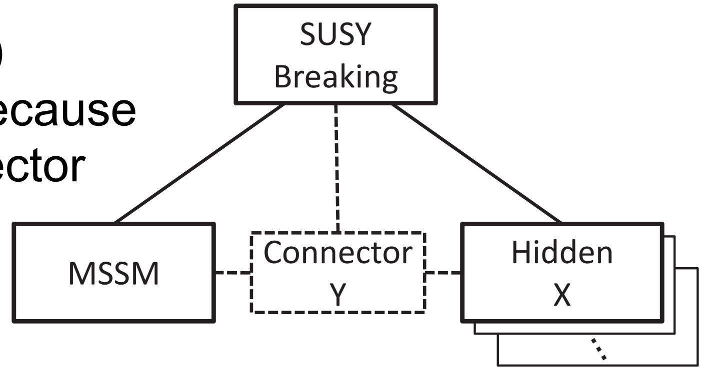
- ~~Freeze Out~~
- Freeze In
  - Hall, et al: 0911.1120
- Assymetric Production
  - Kaplan, Zurek et al: 0901.411

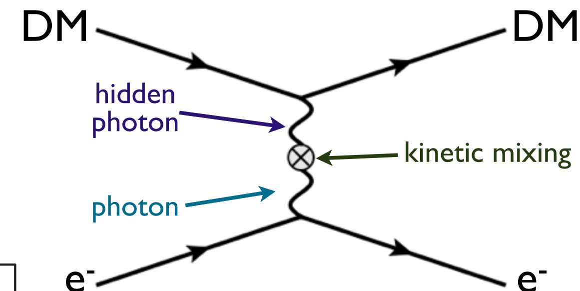


Light Dark Matter: Some Theories

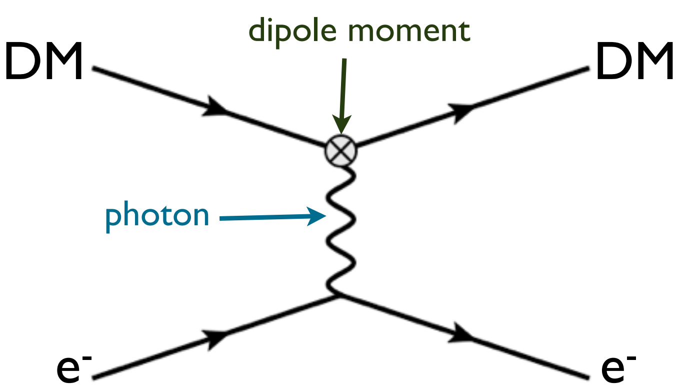
Dark Sector

- Feng & Kumar (0803.4196)
- Not seen at accelerators because of tiny coupling to visible sector





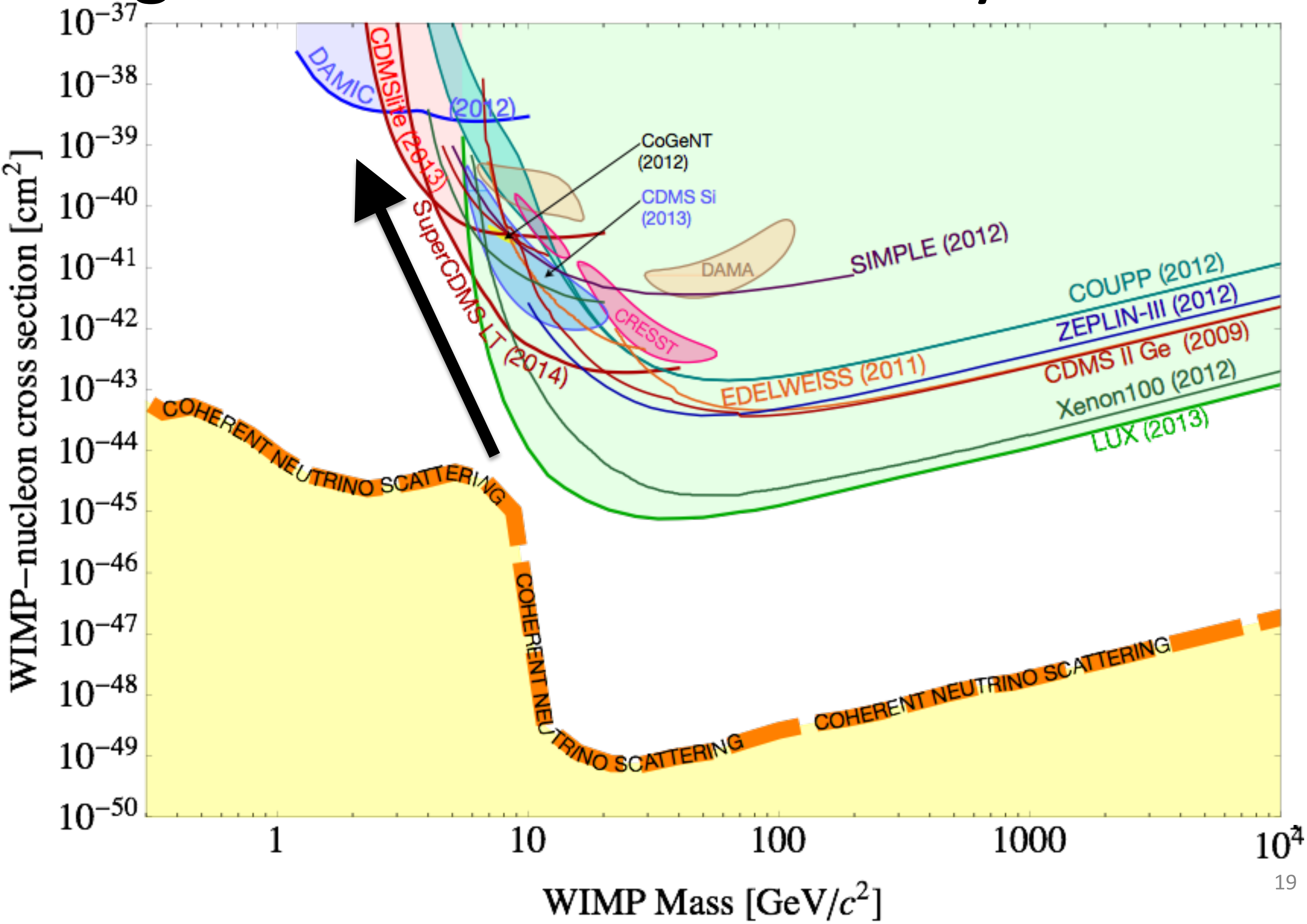
Essig et al: 1108.5383
Lin et al: 1111.0293



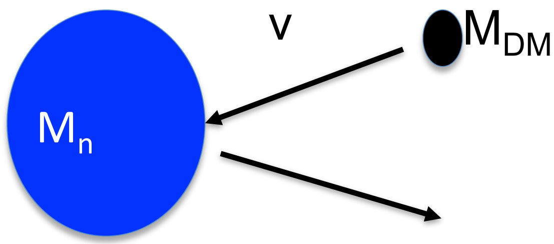
Electric/Magnetic Dipole Coupling DM

- P. Graham, S. Rajendran et al: 1203.2531

Light Mass DM Limits: Why So Bad?



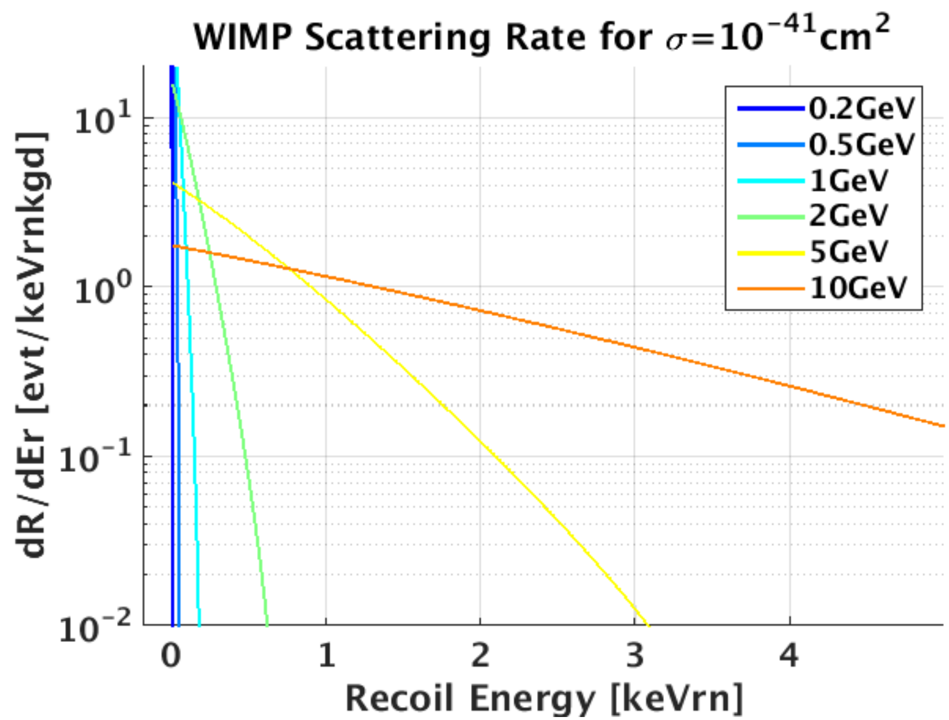
The low-mass Dark Matter Design Driver: Energy Threshold



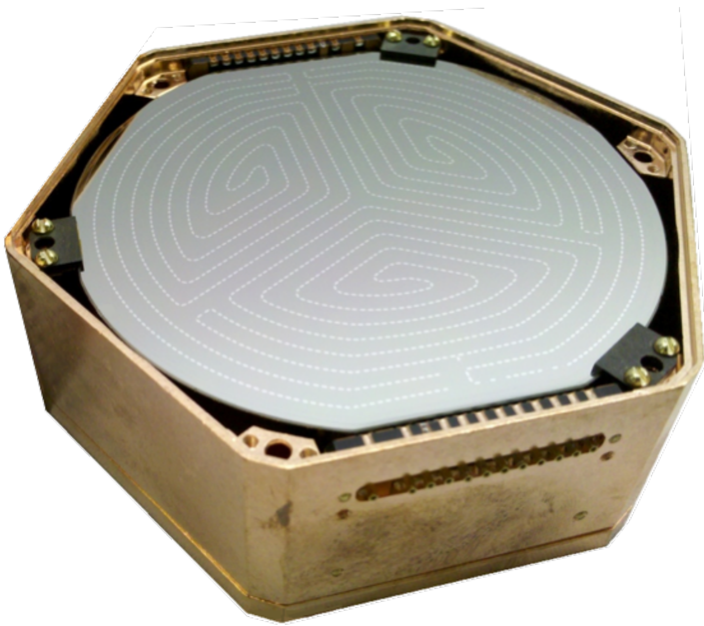
$$\Delta E = \frac{\Delta P^2}{2M_n} \lesssim \frac{2M_{DM}^2 v^2}{M_N}$$

Large M_n:

- Coherent Scattering Rate Enhancement
- Detector must have very low energy thresholds
- self shielding (sometimes)



Light Mass Dark Matter Detectors: 1) Massive Cryogenic Calorimeters

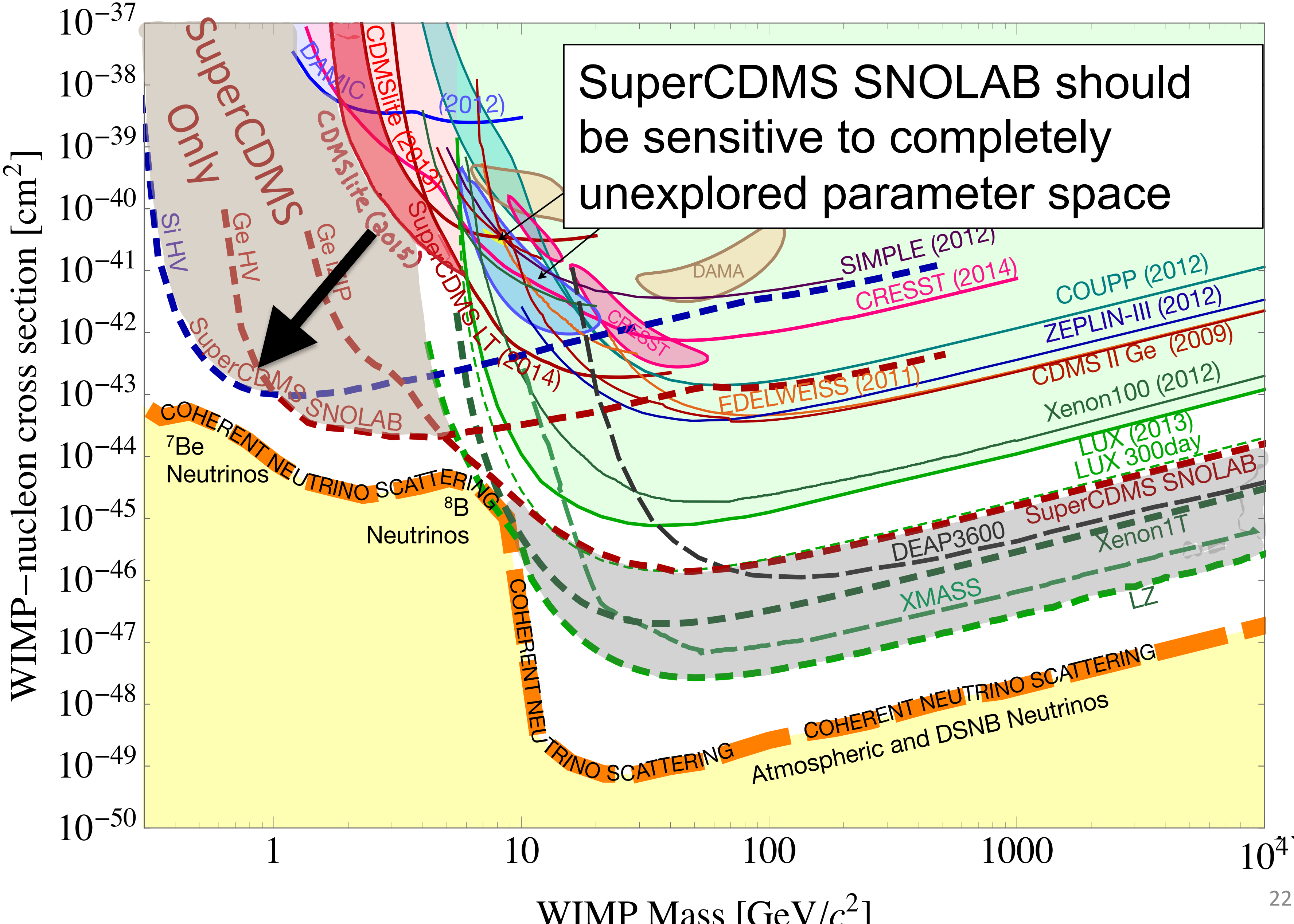


- G2: SuperCDMS SNOLAB
- Insulator / Semiconductor
- Operated near absolute zero (10mK-50mK)
  - Heat Capacities -> 0 @ T=0
  - Stochastic Noise -> 0 @ T=0
- **x10^3 Sensitivity Improvement Potentially Possible**
  - E. Figueroa-Feliciano

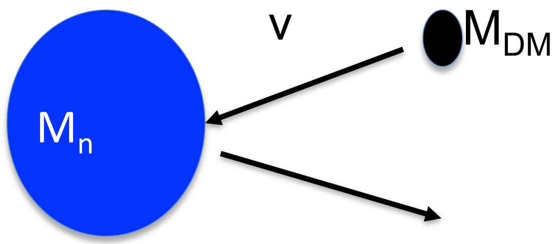
Ionization measurement possible

- ER/NR discrimination
- Luke/Neganov Phonon Ionization Amplifiers
  - N. Mirabolfathi

CDMSlite → SuperCDMS SNOLAB



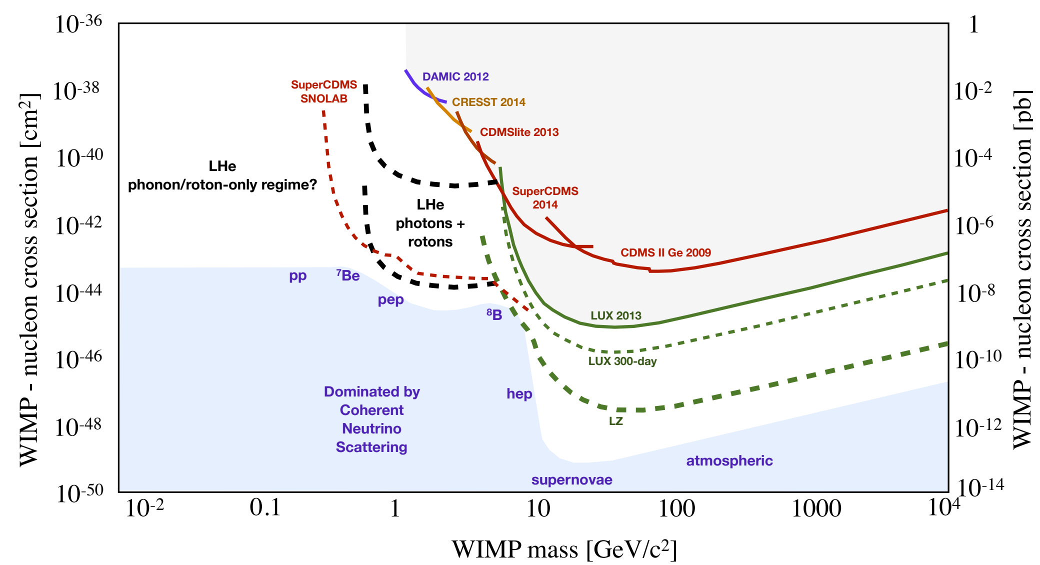
The low-mass Dark Matter Design Driver: Energy Threshold: 2



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

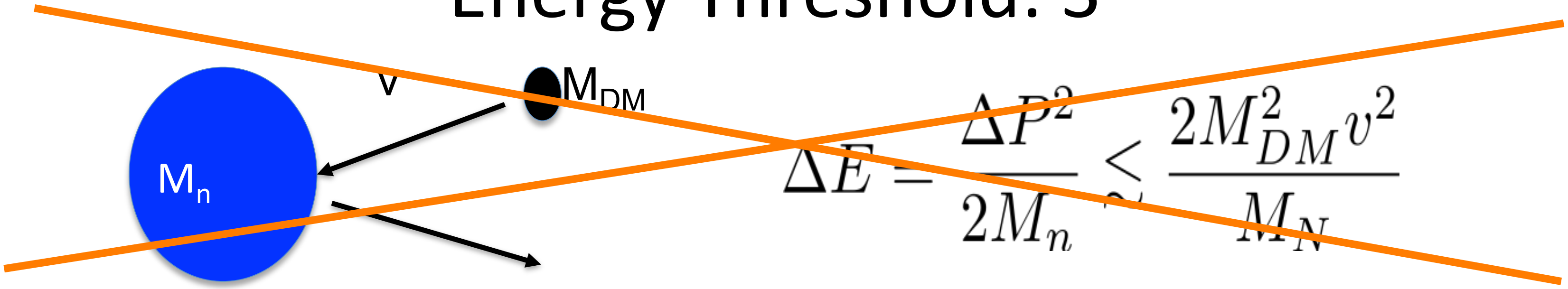
Small M_n:

- ~~Coherent Scattering Rate Enhancement~~
- Detector can have much higher energy thresholds
- D. McKenzie
    - LHe (1302.0534)
    - LNe doped LXe



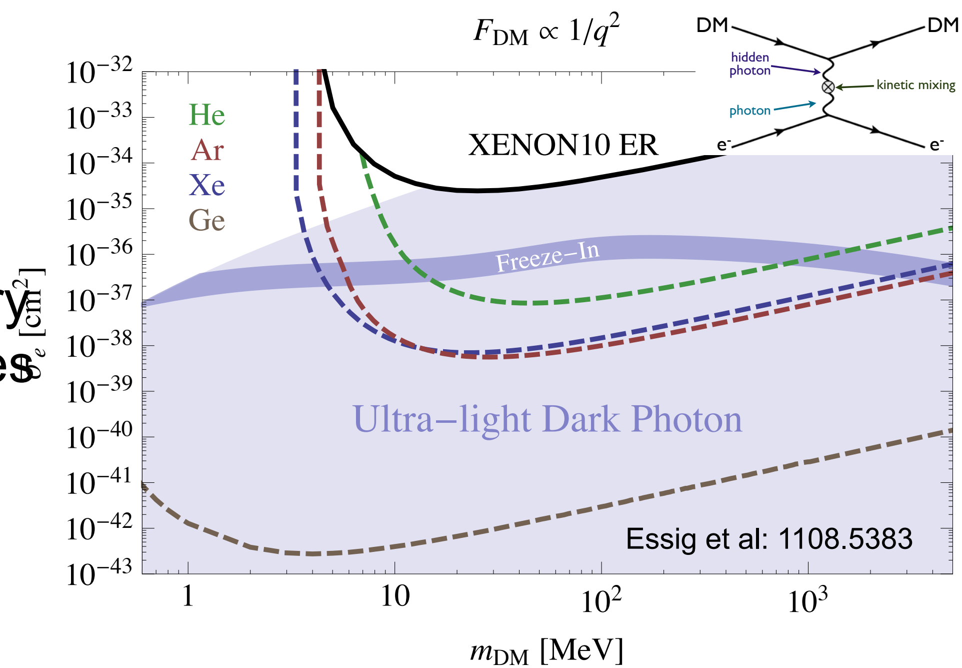
Low Mass Dark Matter: e scattering

Energy Threshold: 3

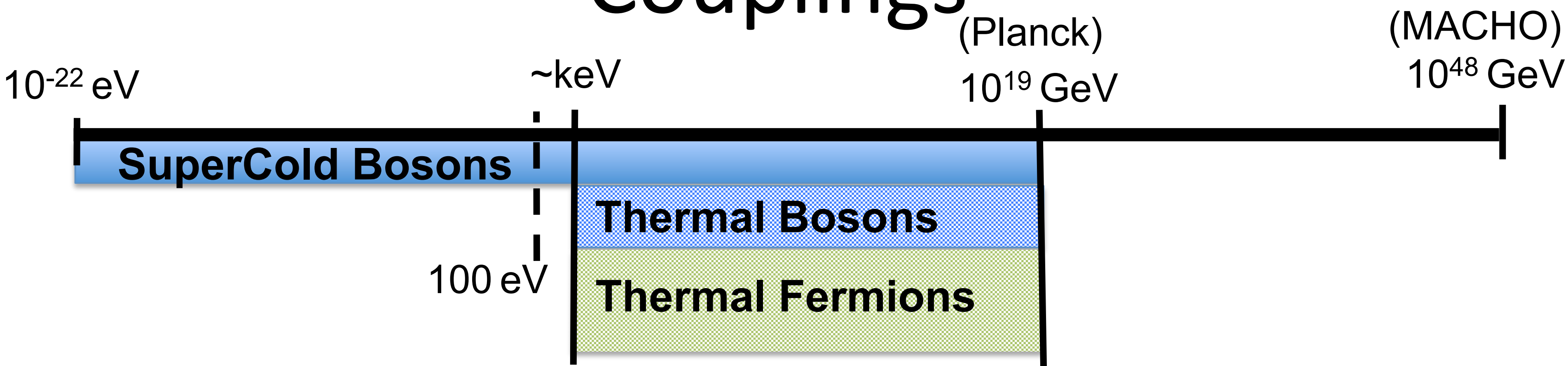


$$DM + e^- \rightarrow DM + e^-$$

- Essig et al. 1108.5383 & 1509.0159
- (J. Mardon)
- Single e^- sensitive detectors
  - 2 Phase TPCs (P. Sorensen)
  - Semicondutor Calorimeters
  - CCDs
- Sensitivity to very light recoils (very light masses) improves as one goes to smaller bandgaps
- Superconductors ?
  - Zurek et al. 1504.07237



Degenerate Boson Dark Matter: Couplings



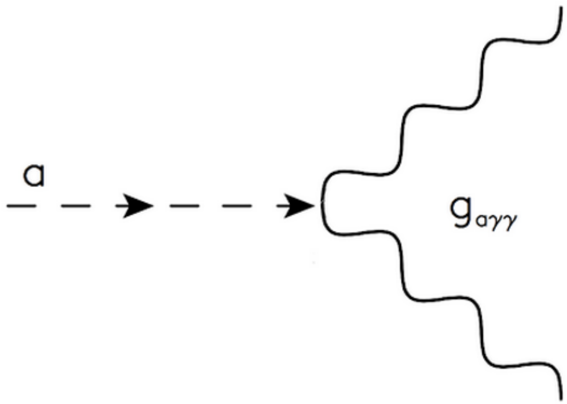
Spin 0 (Axion)	Electromagnetism $\left(\frac{a}{f_a} F\tilde{F}\right)$	Nuclear Force $\left(\frac{a}{f_a} G\tilde{G}\right)$ QCD Axion	Nuclear Spin $\left(\frac{\partial_\mu a}{f_a} \bar{N}\gamma^\mu\gamma_5 N\right)$ General Axions
Spin 1 (Dark Photon)	Nuclear Spin $\left(\frac{F'_{\mu\nu}}{f_a} \bar{N}\sigma^{\mu\nu} N\right)$ Dipole moment	Electro-magnetism $\left(\epsilon F' F\right)$ Kinetic Mixing	Nucleon Current $\left(g A'_\mu J^\mu_{B-L}\right)$ B-L

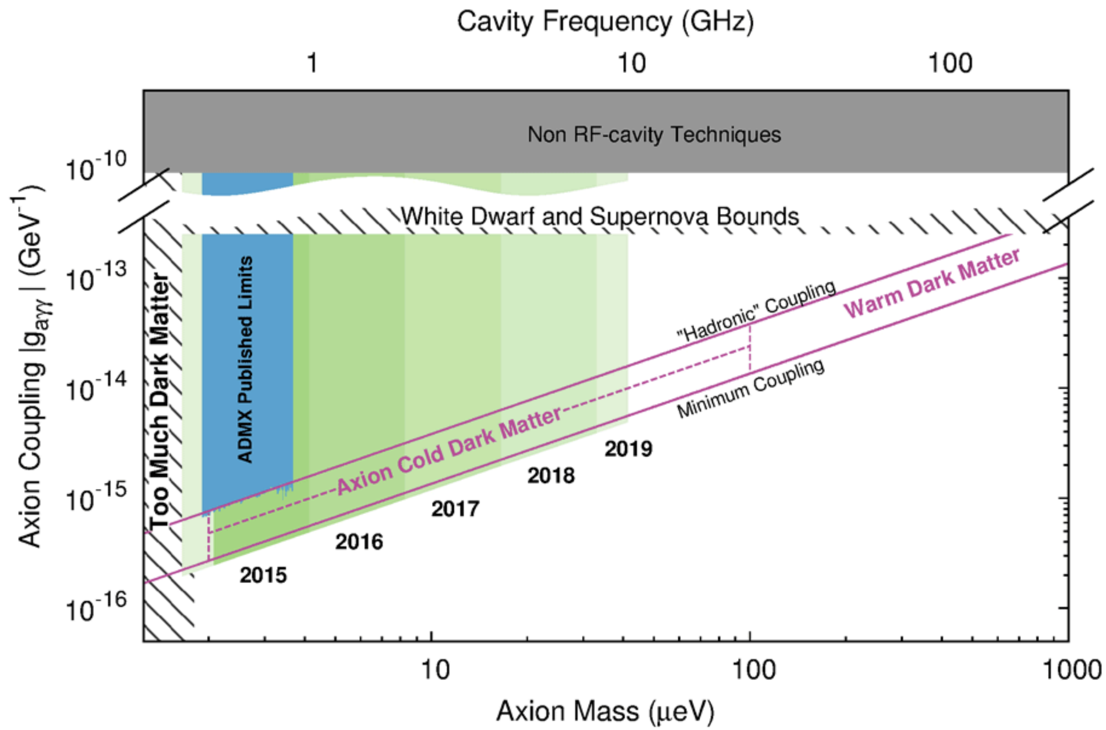
ADMX

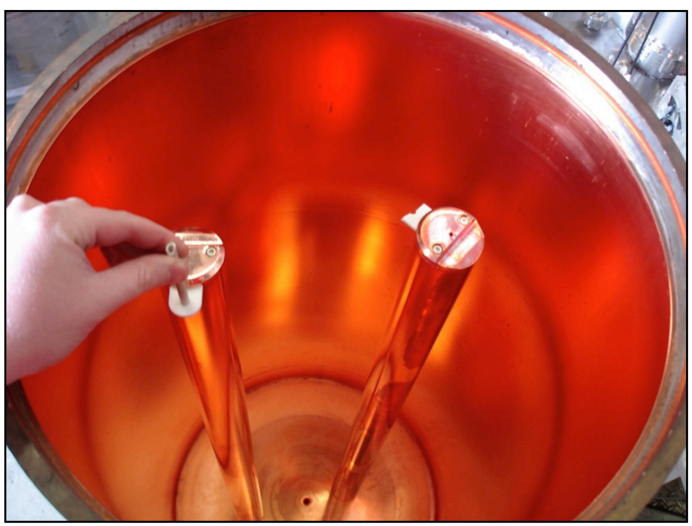
Search for an spin 0 axion field that coupling through

Electromagnetism

$$\left(\frac{a}{f_a} F\tilde{F}\right)$$





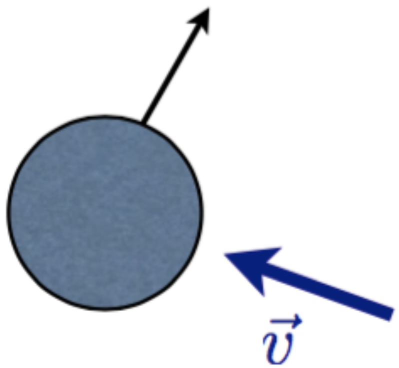


- G2: ADMX
- Talks:
  - G. Carosi
  - J. Sloan

CASPEr

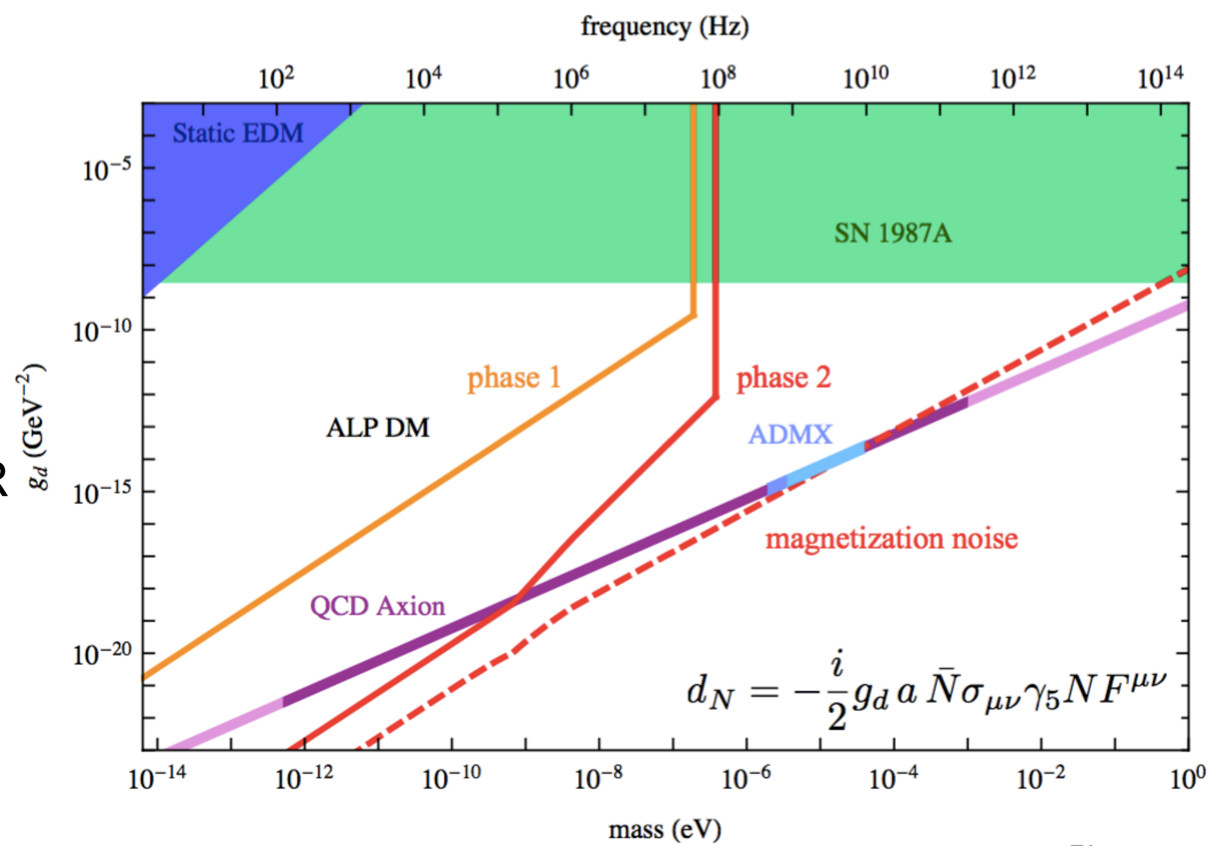
Search for an spin 0 axion field that couples through

Nuclear Force	Nuclear Spin
$\left(\frac{a}{f_a} G\tilde{G}\right)$	$\left(\frac{\partial_\mu a}{f_a}\bar{N}\gamma^\mu\gamma_5 N\right)$
QCD Axion	General Axions



$$H_N \supset \frac{a}{f_a}\vec{v_a}.\vec{S}_N$$

- Leverage enormous sensitivity of SQUIDs / NMR to search for DM
- Fully complementary to ADMX
- S. Rajendran
  1306.6089
  1306.6088
  1101.2691

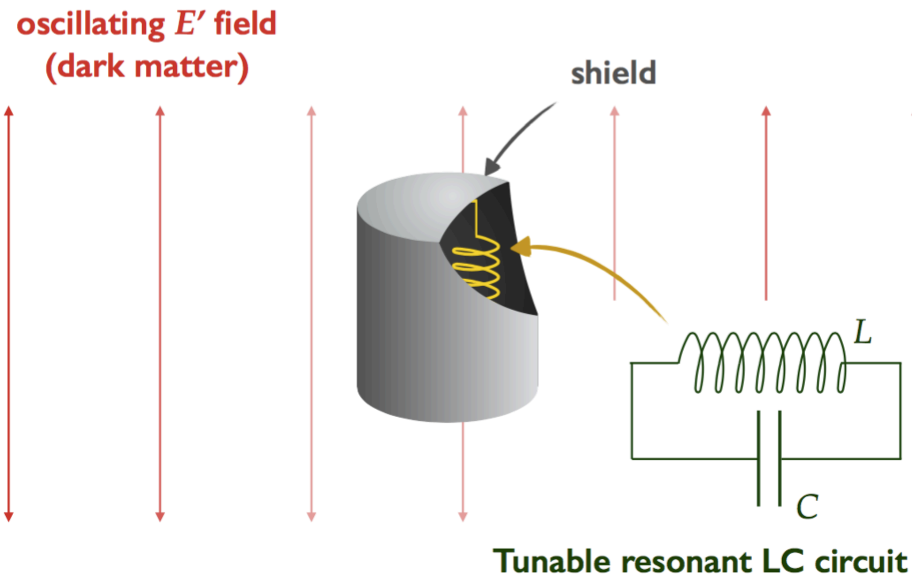


DM Radio

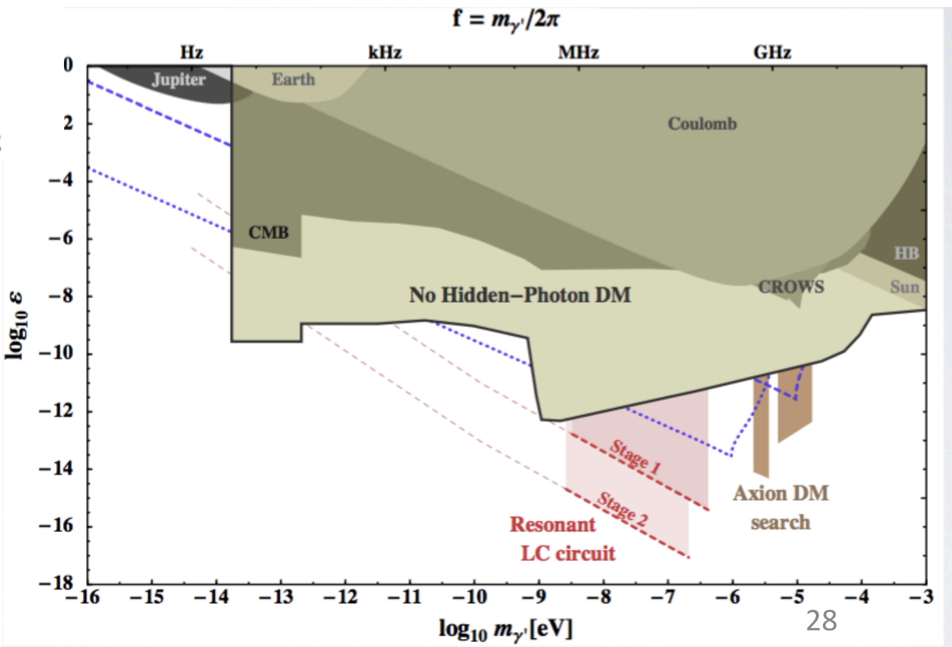
Search for an spin 1 dark photon field that couples through

Electro-magnetism

$$\left(\epsilon F' F\right)$$



- Leverage enormous sensitivity of SQUIDs to search for DM
- S. Rajendran
  J. Mardon
  S. Chaudhuri
  1411.7382



Conclusions

- A really exciting next decade in Dark Matter Searches:
  - LHC
  - G2 Direct Detection program
- If WIMPs not found: Search Everywhere
- Dark Matter sensitivity fundamentally linked to detector technology improvements and new experimental ideas
  - CASPEr
  - DM Radio
  - Improving energy thresholds by many orders of magnitude in calorimeters
-

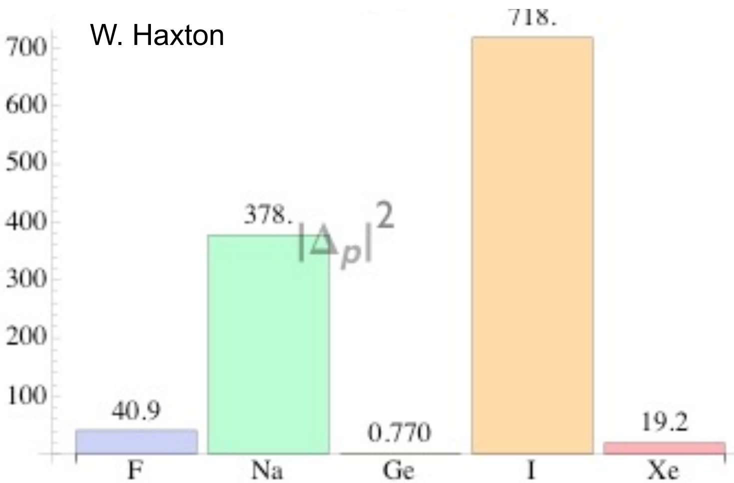
Things I should have talked about but didn't have time

- Black Holes / Q Balls / Dark Matter Nuclei
- Different Scattering Interactions (EFT)
- Light Mass Beam Dump / Fixed Target Experiments
- Indirect Detection

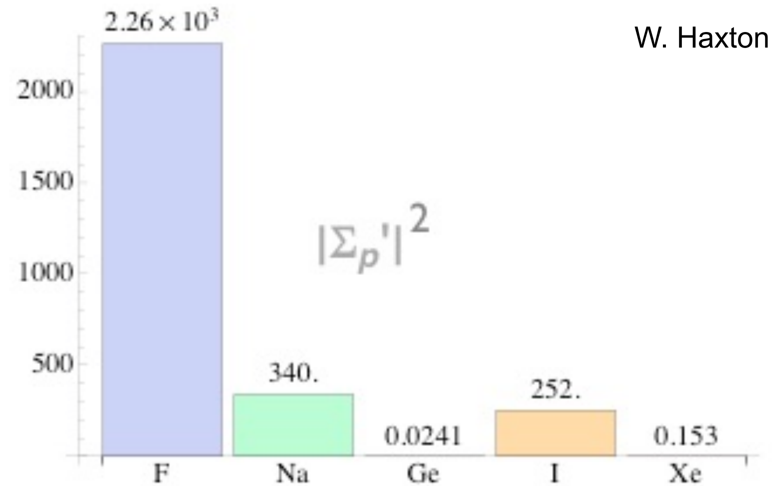
Backup

EFT: Different Operators

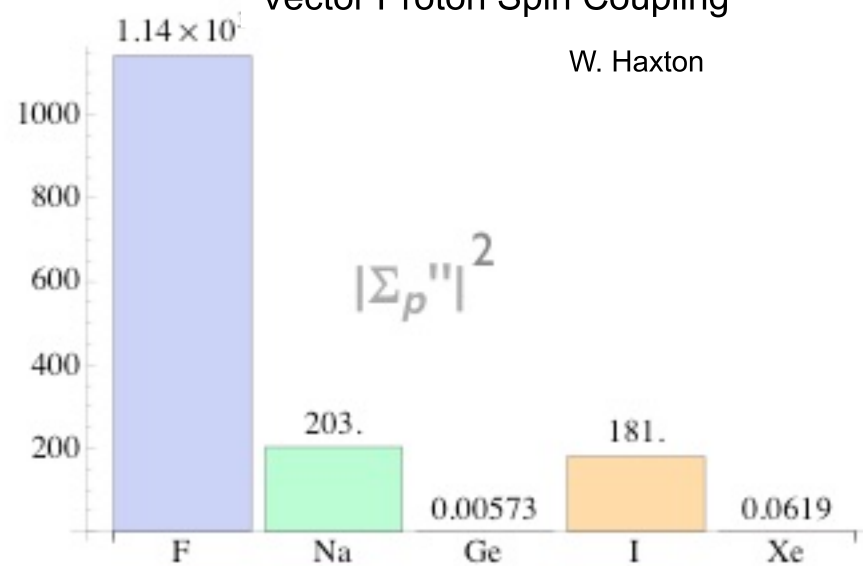
Orbital Angular Momentum Coupling



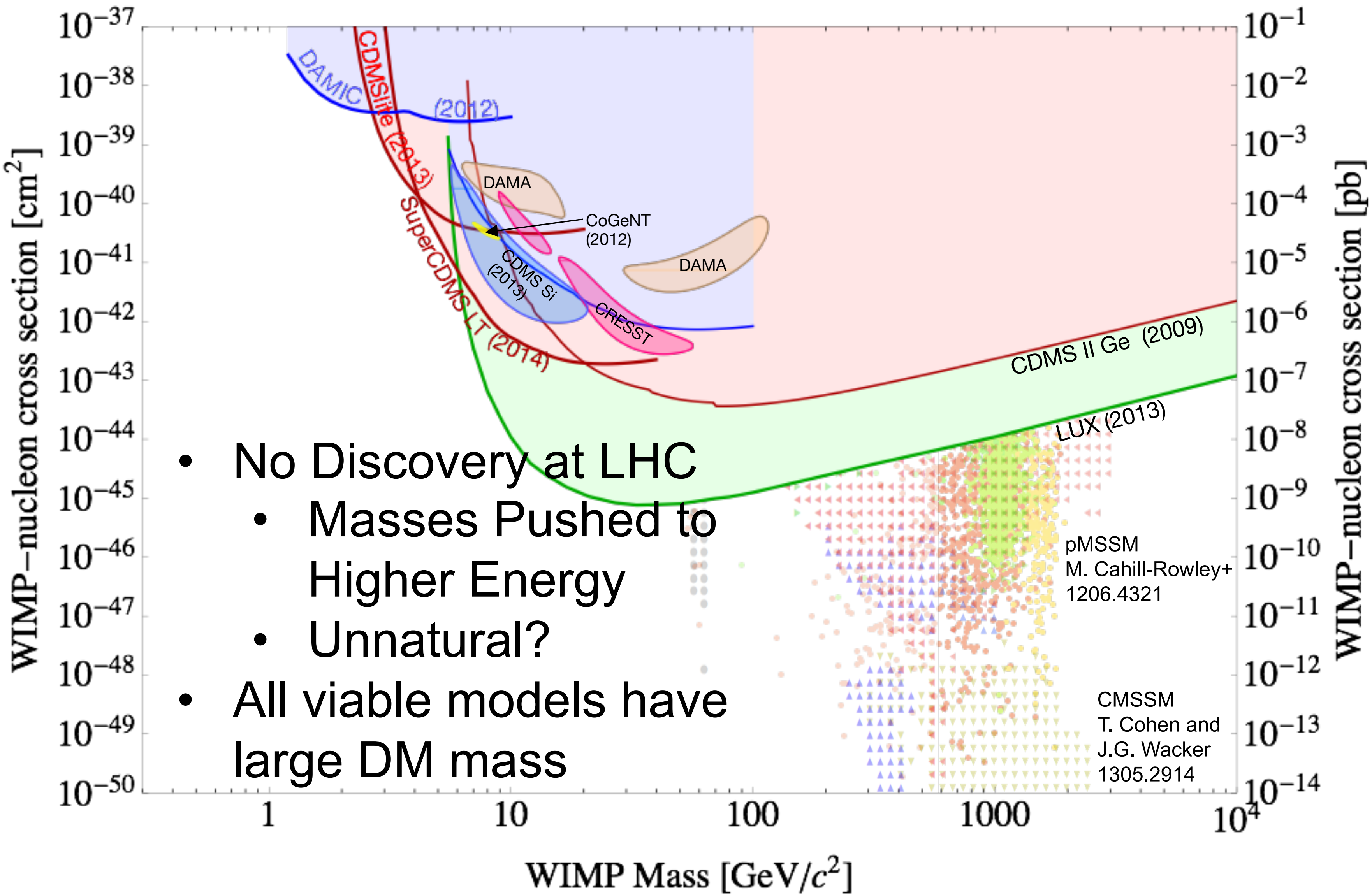
Vector (Transverse) Proton Spin Coupling



Vector Proton Spin Coupling

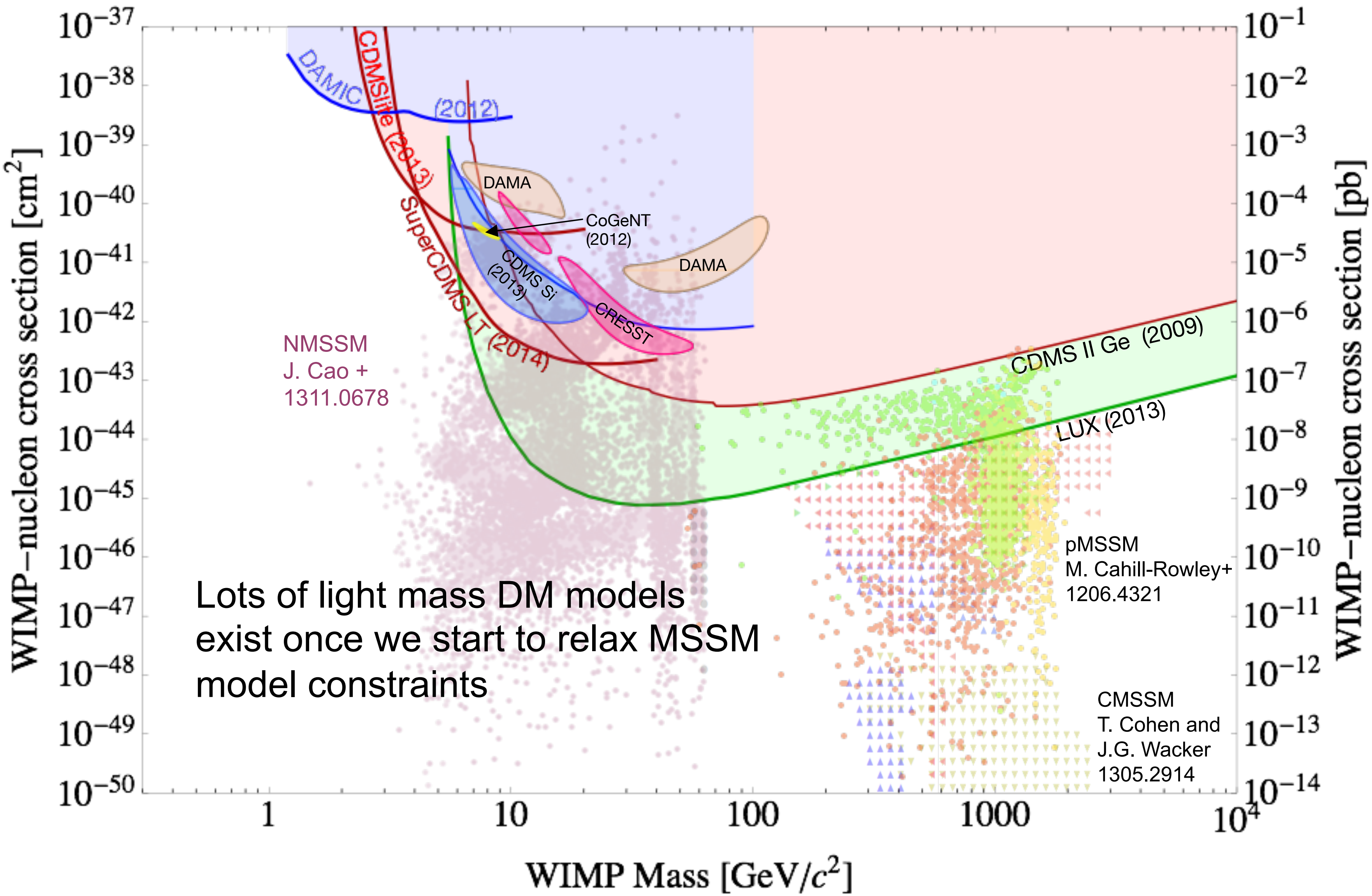


pMSSM & cMSSM Direct Detection Scattering Rates: Theory & Experiment Limits

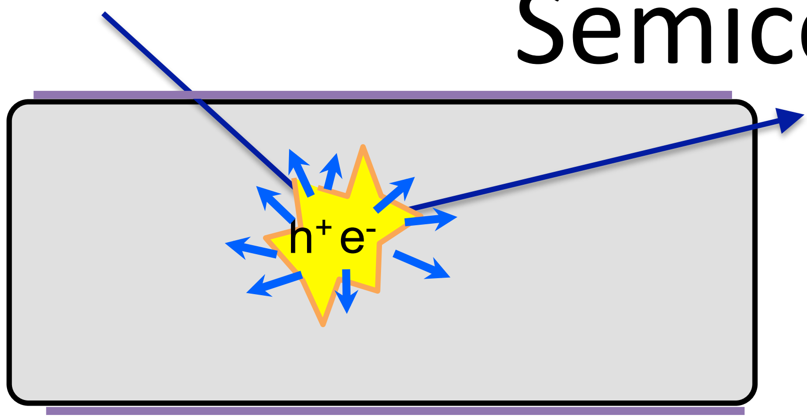


- No Discovery at LHC
  - Masses Pushed to Higher Energy
  - Unnatural?
- All viable models have large DM mass

nMSSM Direct Detection Scattering Rates
Theory & Experiment Limits



Interaction Products in Semiconductors

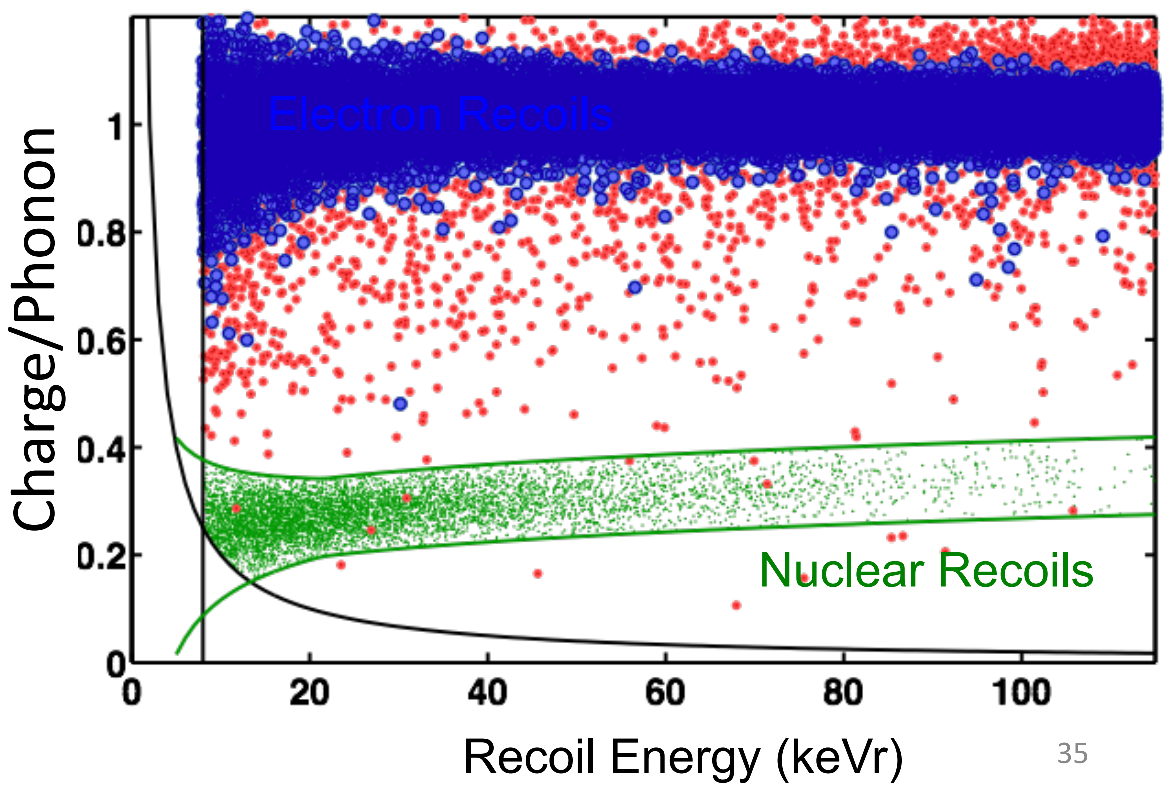


Nuclear Recoils (NR)

- 8% e^-/h^+
- 92% phonons

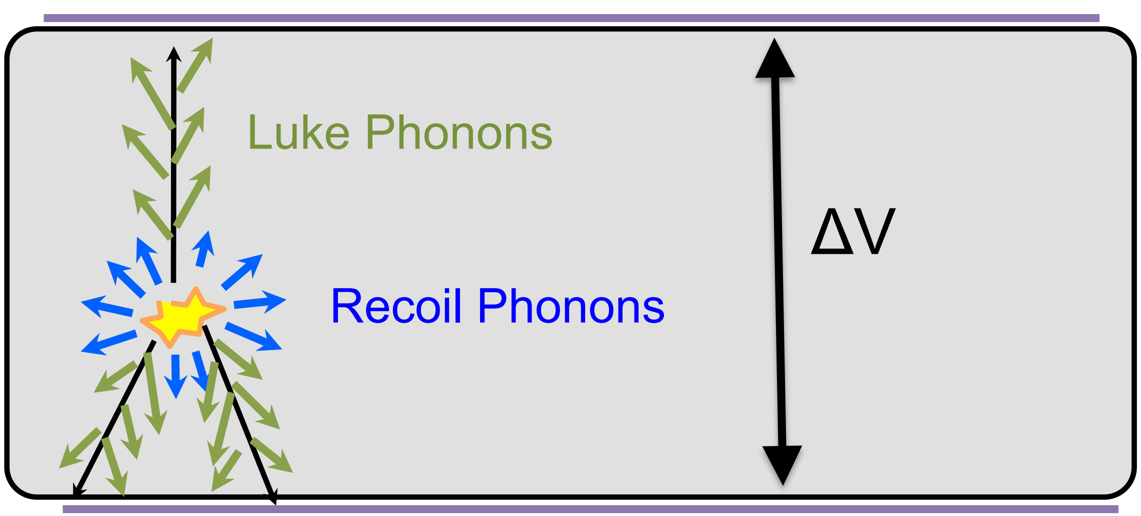
Electron Recoils (ER)

- 25% e^-/h^+
- 75% phonons



Luke-Neganov Phonon Production

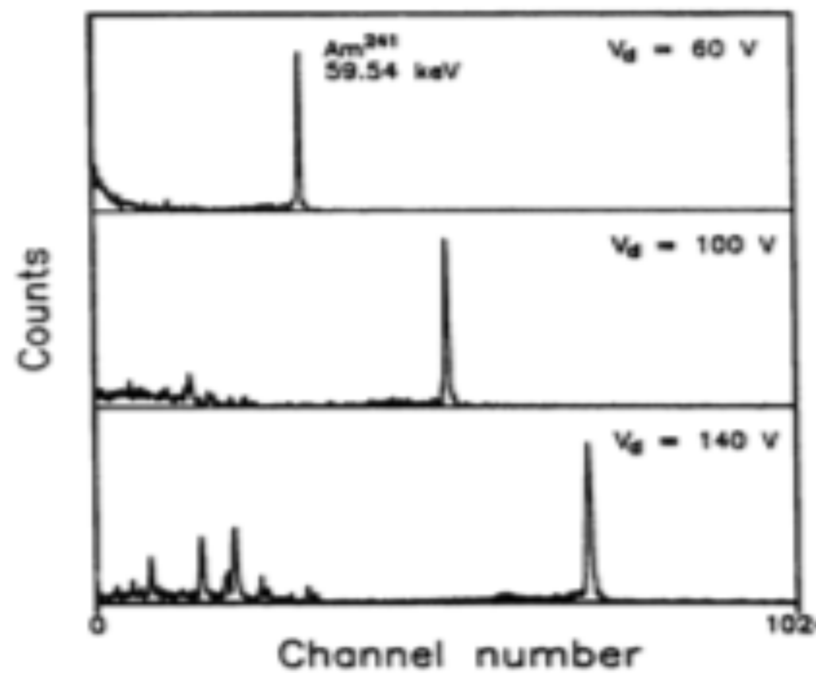
- Drifting charges release kinetic energy via Luke-Neganov Phonon Production
- $$E_{total} = E_{recoil} + E_{luke}$$
  $$= E_{recoil} + Qe\Delta V$$



Detector Design #2: Luke Neganov Ionization Amplifier

$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + Qe\Delta V$$

$$\lim_{\Delta V \to \infty} E_{total} \propto Q$$



P.N. Luke et al. NIM A289, 405 (1990)

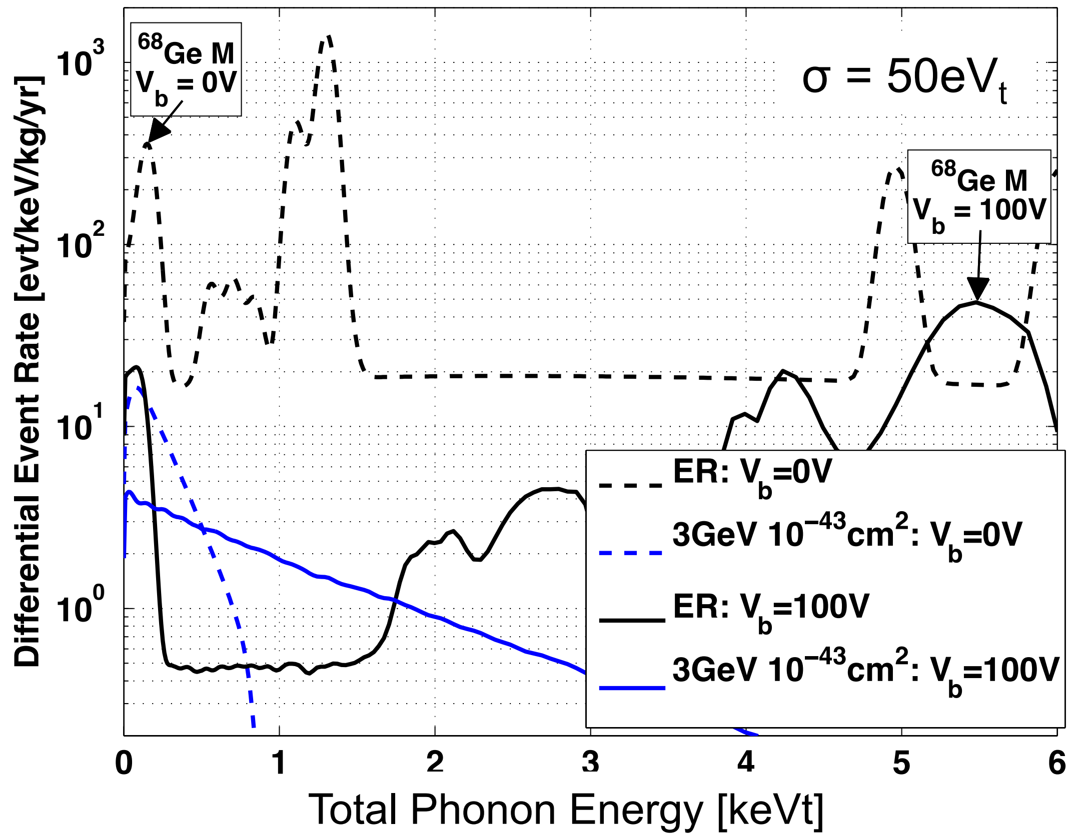
At high voltage

- Bad: No ER/NR discrimination through Ionization Yield
- Good: You've made a phonon amplifier for charge

Preferential Stretching of Electronic Recoils

$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + Qe\Delta V$$
$$= E_{recoil}\left(1 + \frac{Ye\Delta V}{< E_{eh} >}\right)$$

Since Electronic Recoils (ER) have larger Ionization Yields than Nuclear Recoils (NR), they have larger Luke Neganov Gain

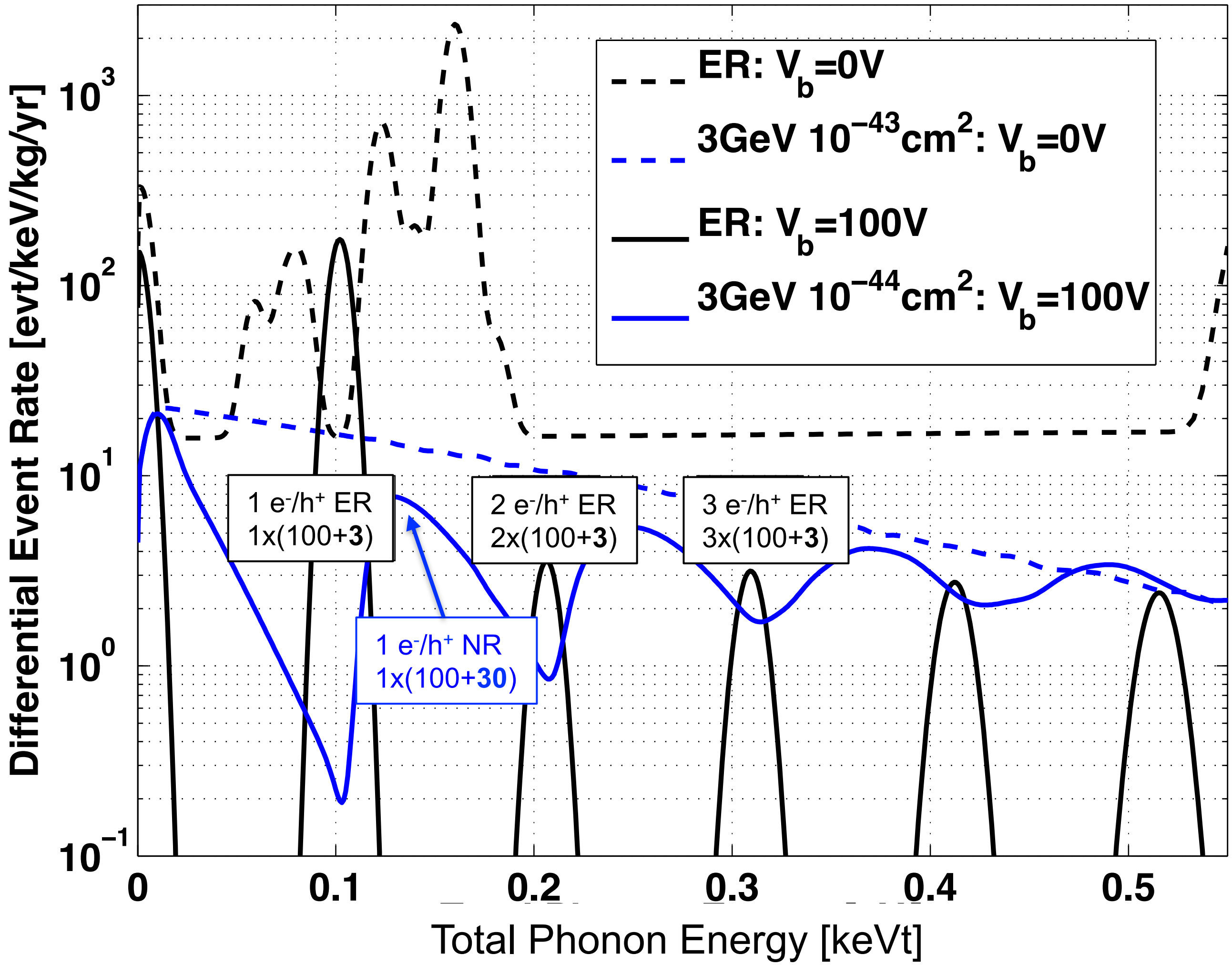


If you have phonon sensitivity to spare, this is great!

ER/NR Stretching: The Single e^-/h^+ Limit

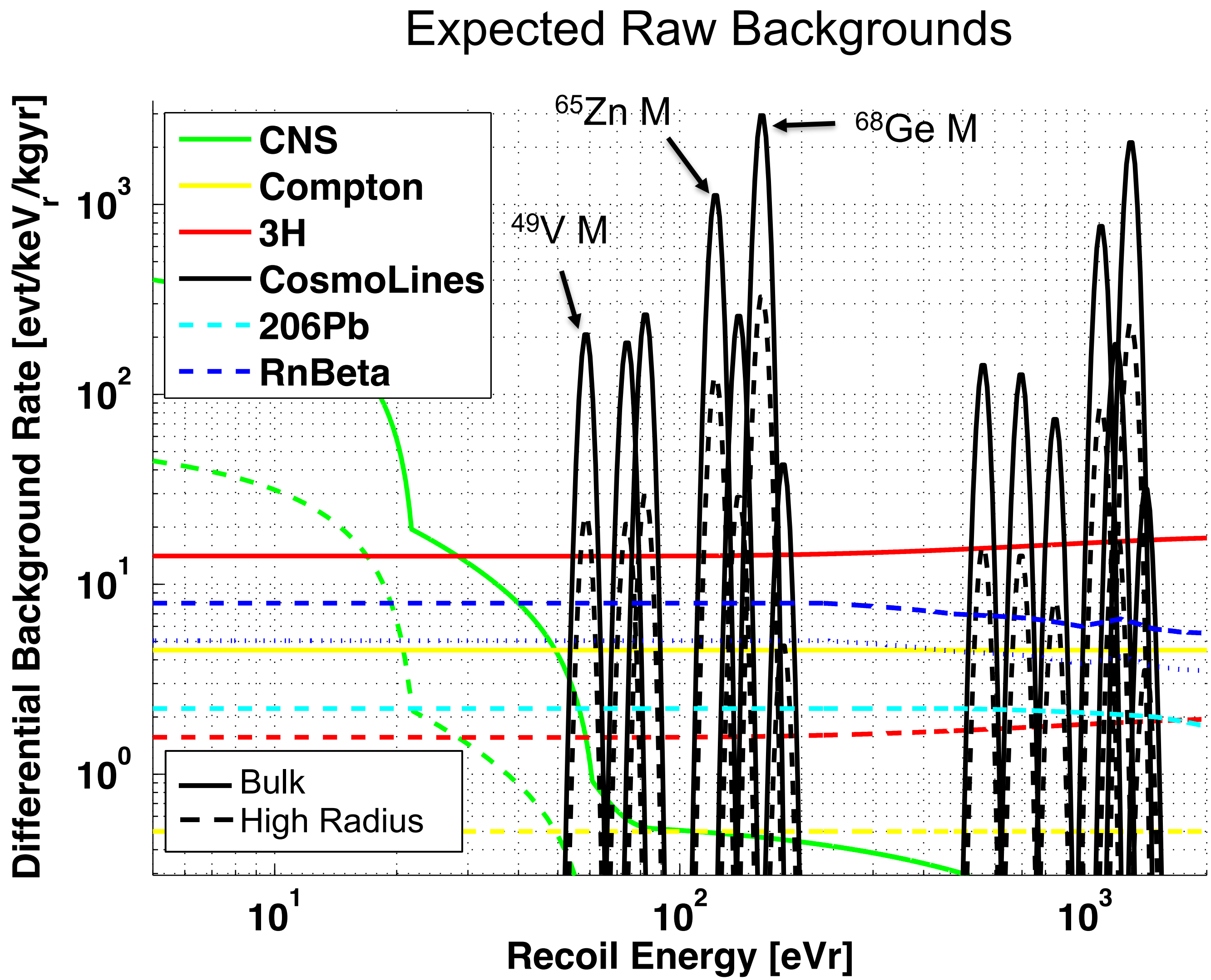
- σ = 5eV$_t$
- Single e^-/h^+ Sensitivity
- ER/NR Discrimination

$$E_{total} = E_{recoil} + E_{luke} \\ = E_{recoil} + Qe\Delta V$$



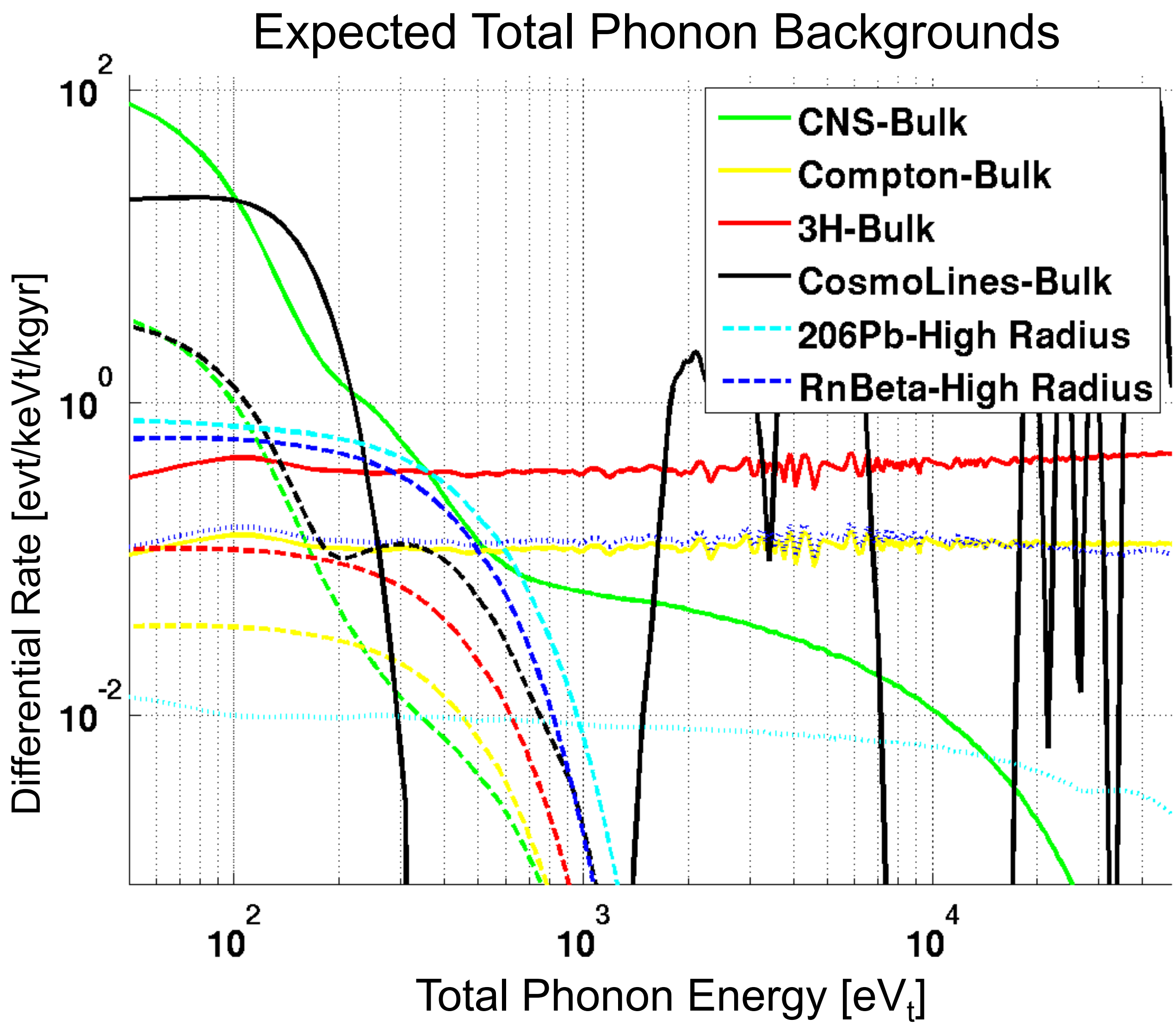
SuperCDMS HV Sensitivity Estimates

Exposure	16.5kgyr
Compton Background	5 evt/ keVrkgyr
^{3}H Background	3 months @ surface
Radon Background Cu (alpha)	5.6mBq/m^2



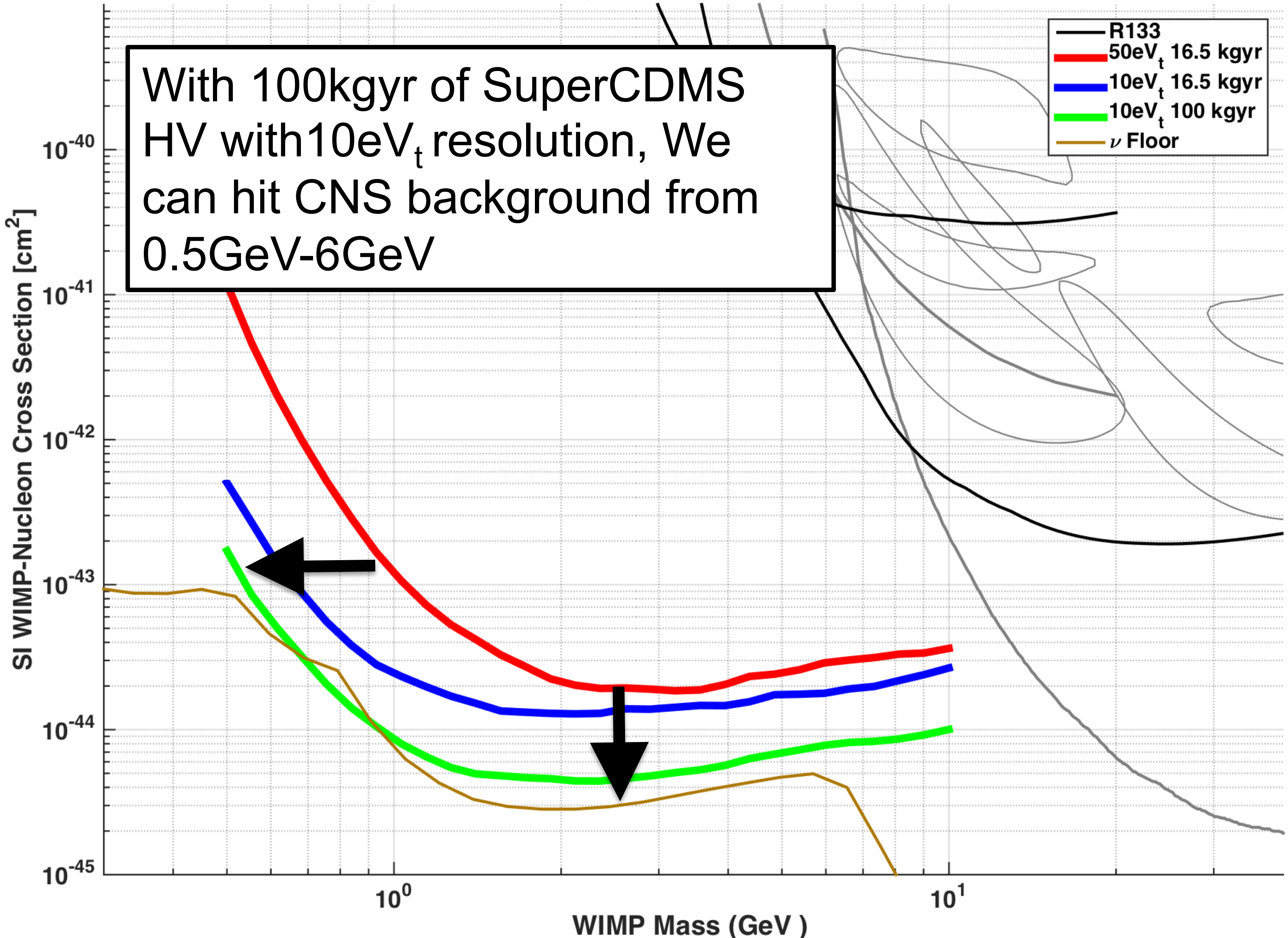
SuperCDMS HV Sensitivity Estimates

Exposure	16.5kgyr
Compton Background	5 evt/ keVrkgyr
^3H Background	3 months @ surface
Radon Background Cu (alpha)	5.6mBq/m^2
Voltage Bias	**100V**
Phonon Resolution	**50eV$_t$**
Trigger Threshold	7σ

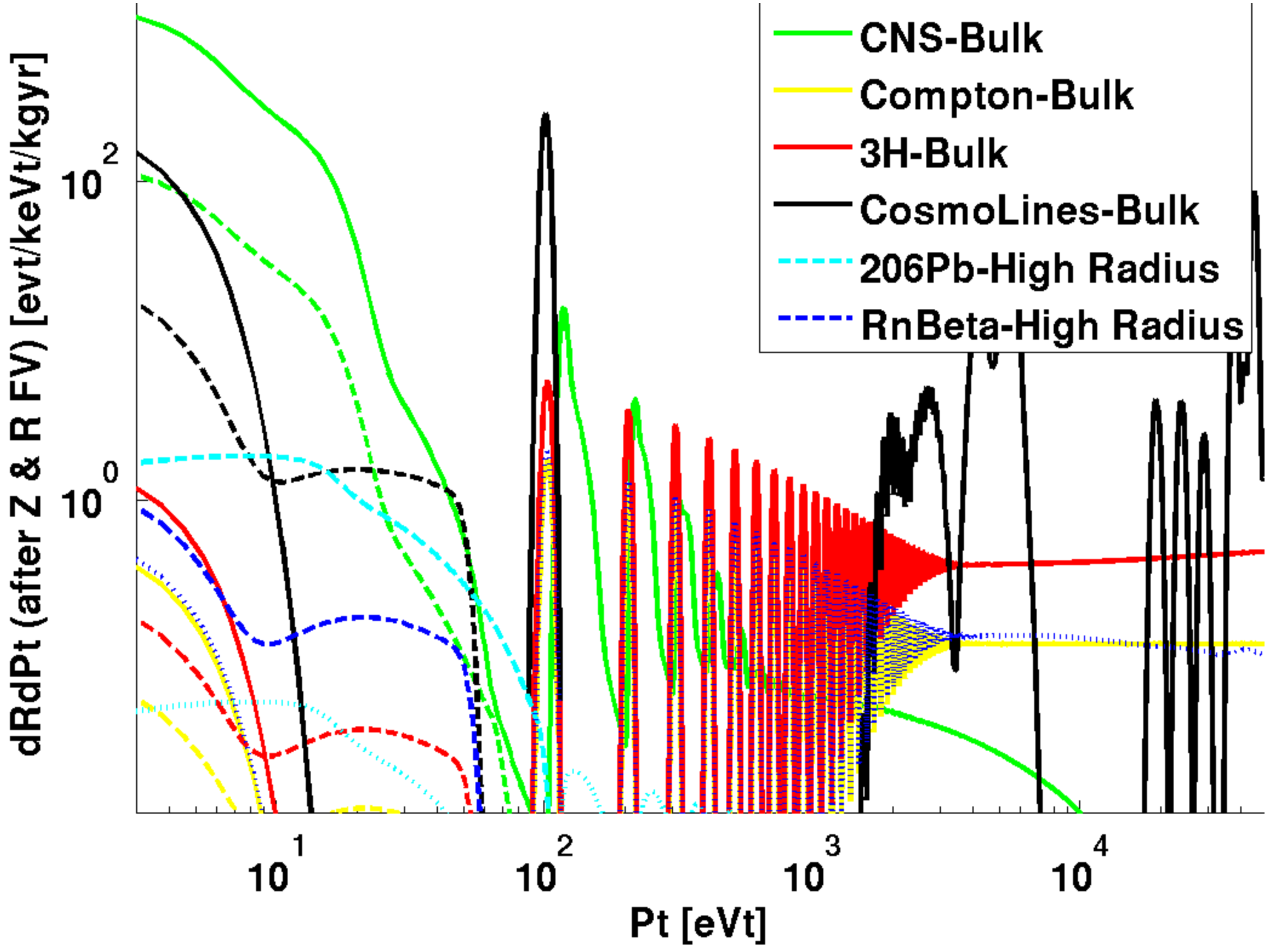


G2+: Improving Phonon Resolution

With 100kgyr of SuperCDMS HV with 10eV$_t$ resolution, We can hit CNS background from 0.5GeV-6GeV

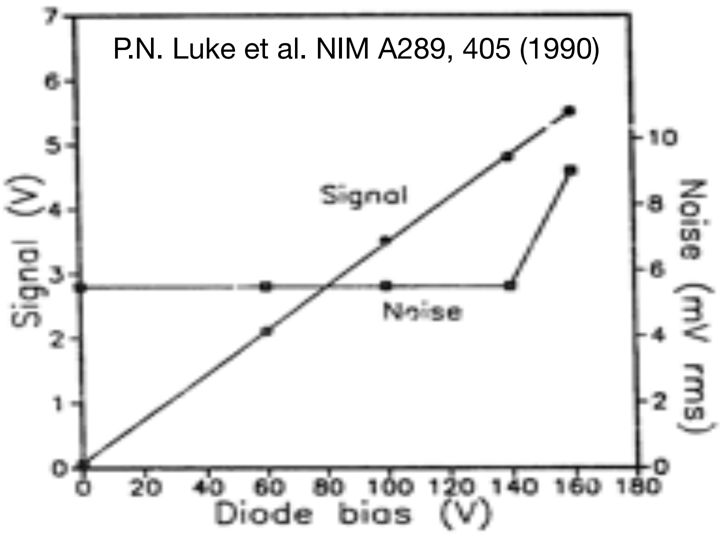


SuperCDMS HV ER Search



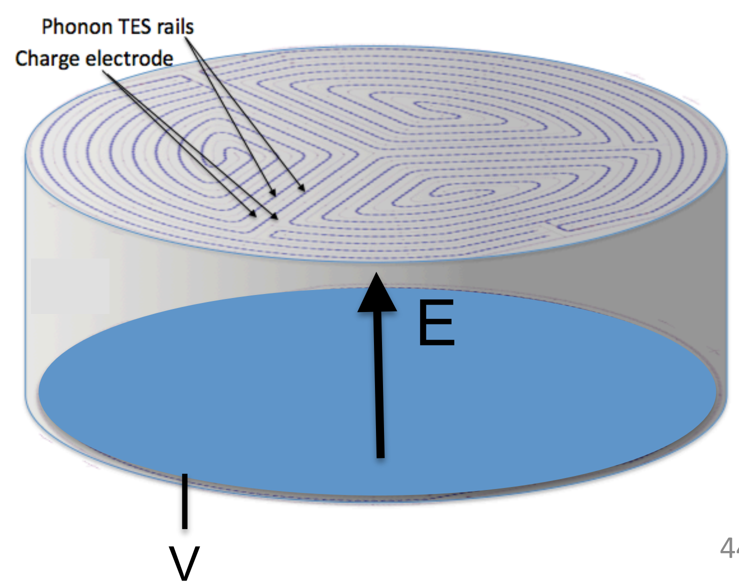
Signal = Electron Recoils
Background = Nuclear Recoils

∞ Luke-Neganov Gain?



- Charge Breakdown Limits Luke-Neganov Gain
- What's $V_{breakdown}$ for our detectors?
- Test Setup: Unplug 1 side of an iZIP

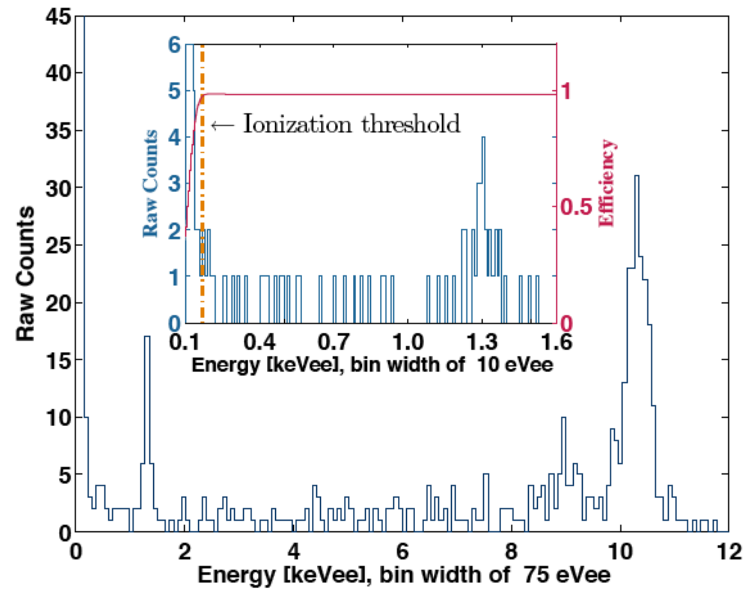
- $E_{breakdown}$ ~ 27V/cm (69V)
- This is a really low breakdown field (Potential For Huge Improvement)

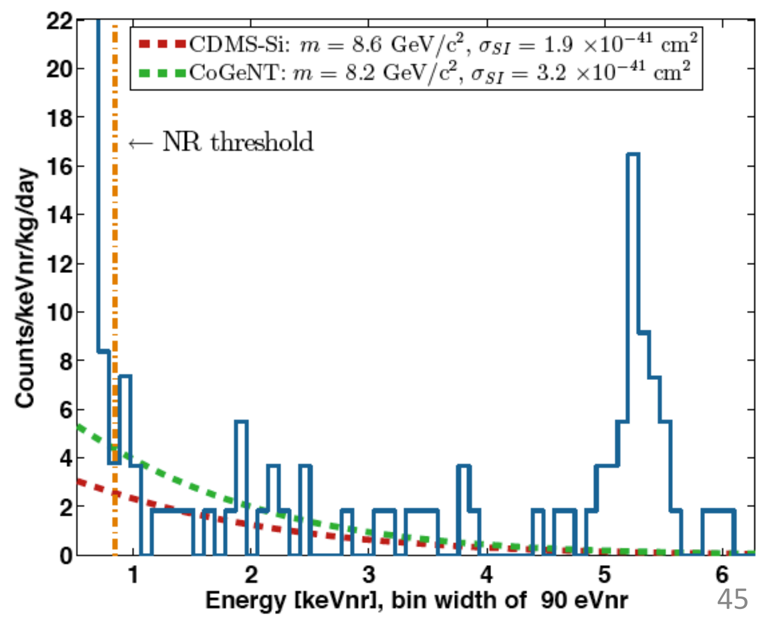


CDMSlite: “low ionization threshold experiment”

- Measured $\sigma_q = 14eV_{ee}$

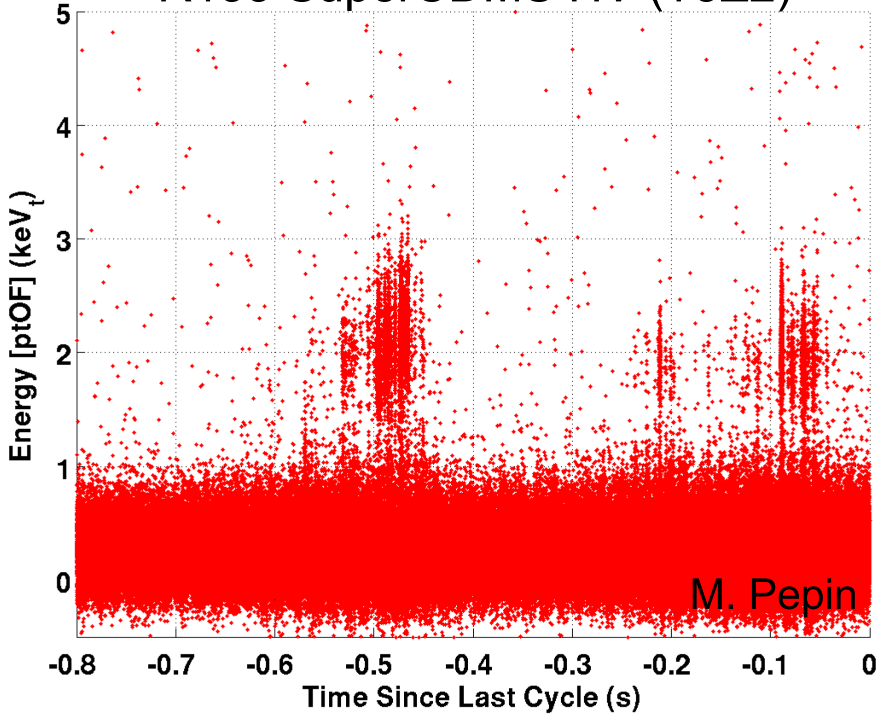
  $\sigma_{pt} = 340eV_t$
  - YIKES! x7 worse than SuperCDMS SNOLAB specs
  - CoGENT: $\sigma_q = 50eV_{ee}$
  - √2 due to unplugging ½ the phonon sensors
- Threshold: 12 σ_{pt}
  - YIKES! 6-7σ
- 6kgd Exposure
- Only Quality Cuts
- PRL **112**, 041302 (2014)





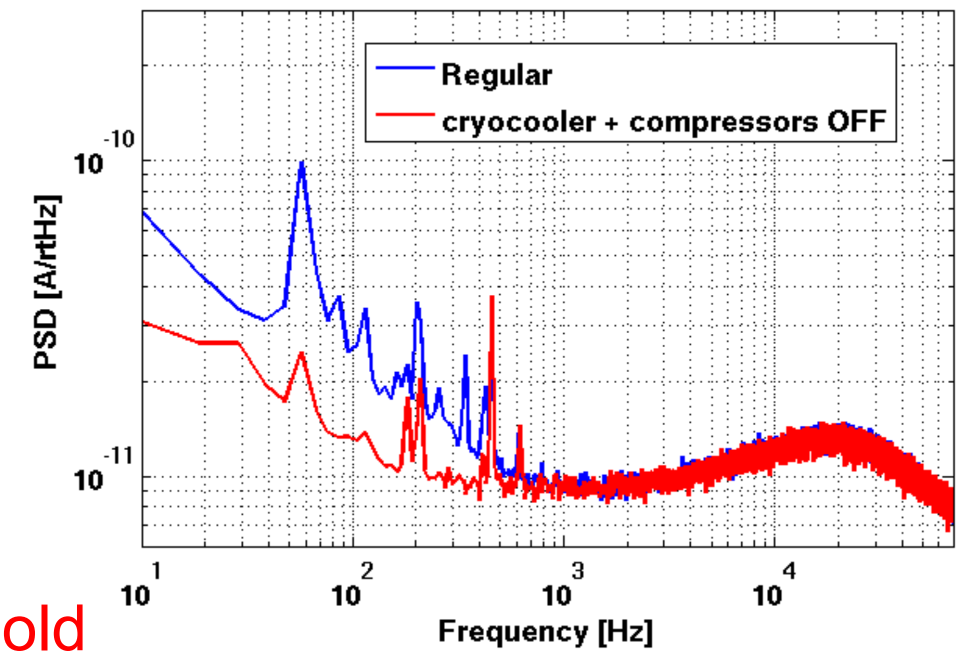
Why So Large: Vibrational Noise!

Baseline Noise vs Time
R133 SuperCDMS HV (T5Z2)



Vibrations from the cryocooler produce high frequency phonons within our detectors which look like real events.

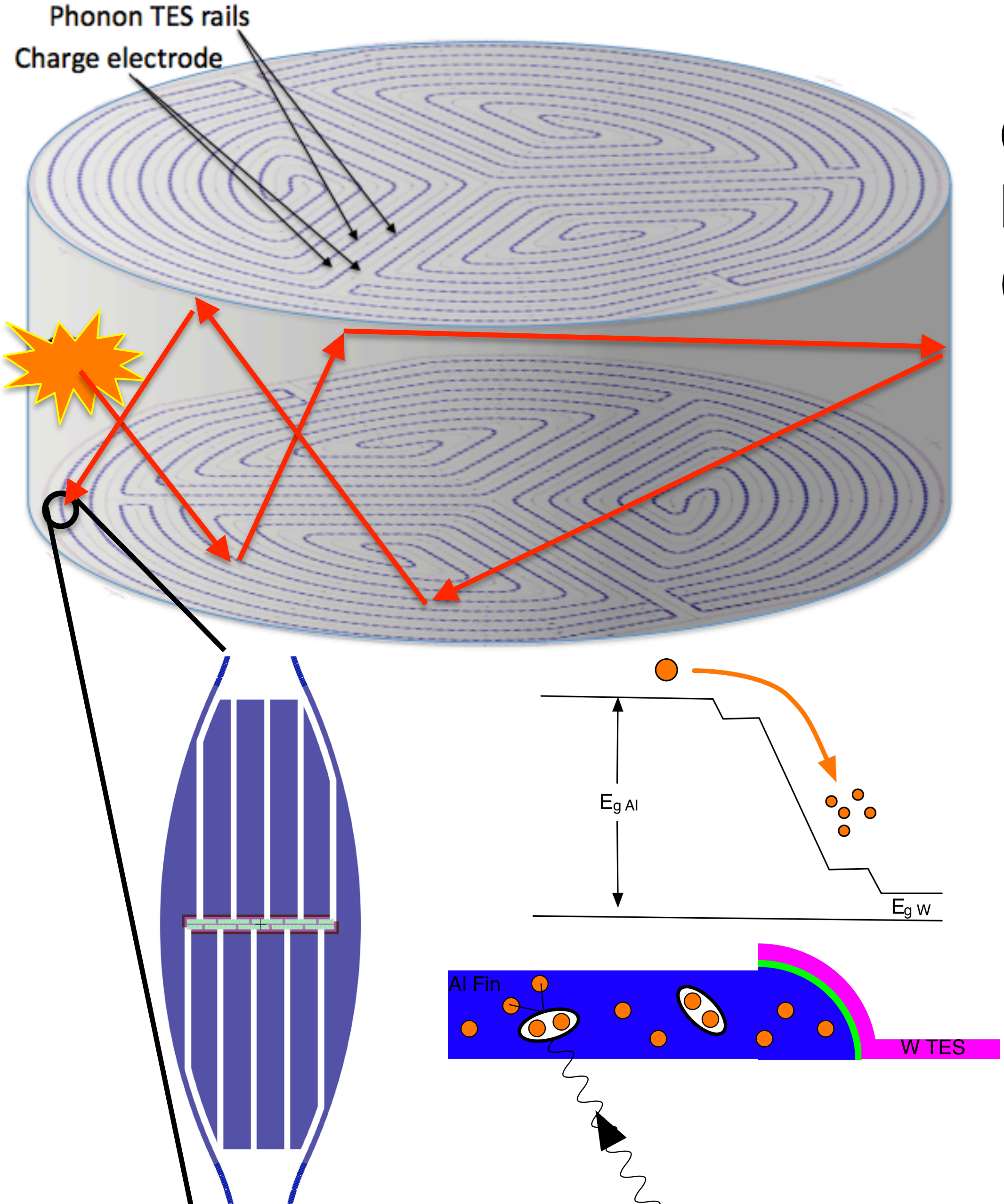
Baseline Noise PSD (T5Z2D)



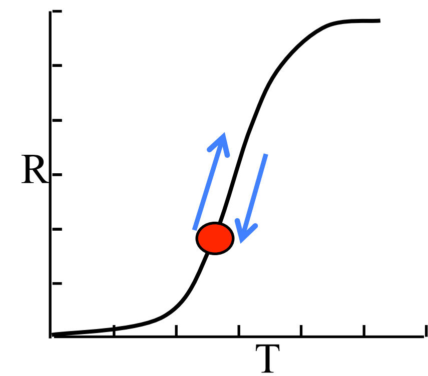
Toggle CryoCooler ON/OFF

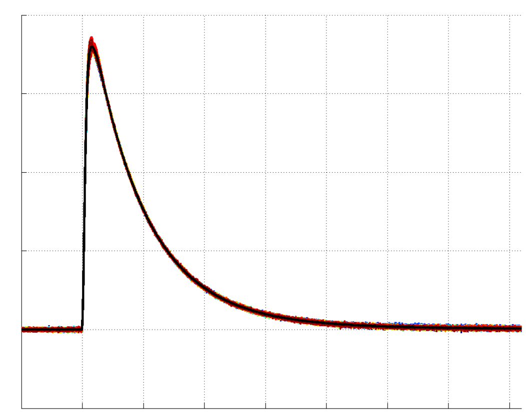
- Threshold: $12\sigma_{pt}$ ➞ $7\sigma_{pt}$ (?)
- $\sigma_{pt:}$ 340eVt ➞ 90eVt
- Caveats:
  - Study done at 0V
  - Trigger vs Analysis Threshold

Athermal Phonon Sensors

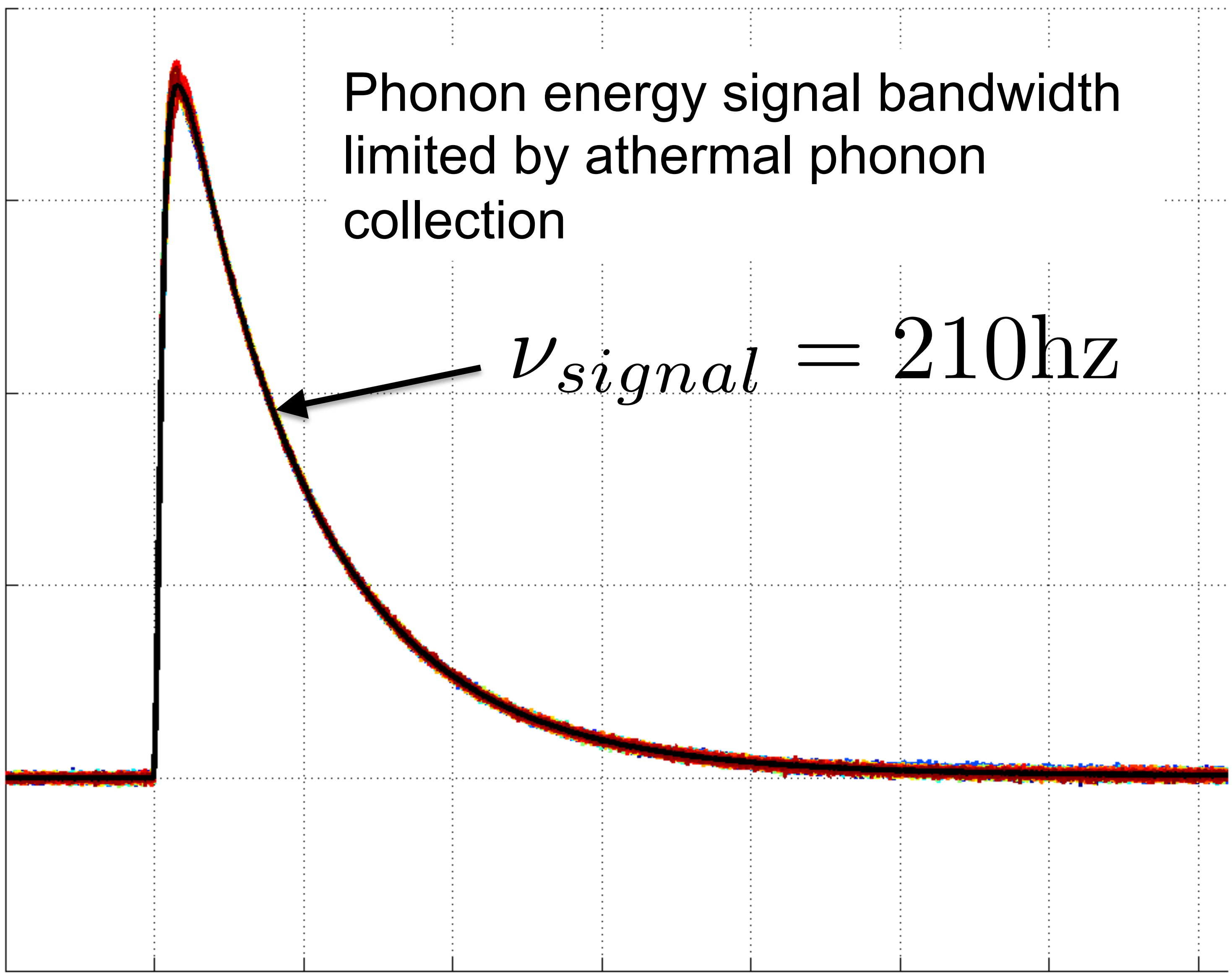


Collect and Concentrate Phonon Energy into W TES (Transition Edge Sensor)

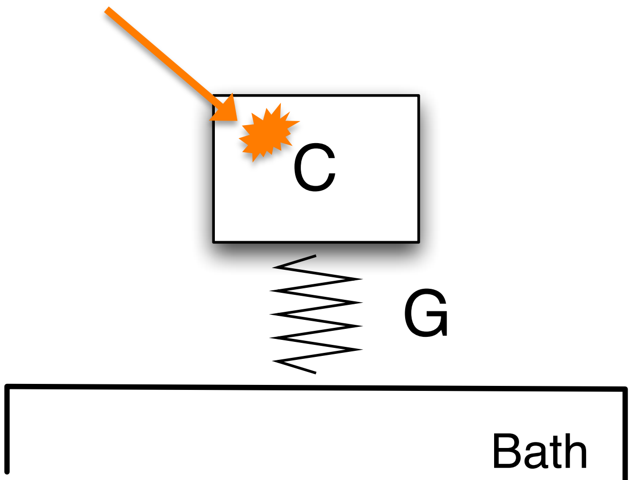


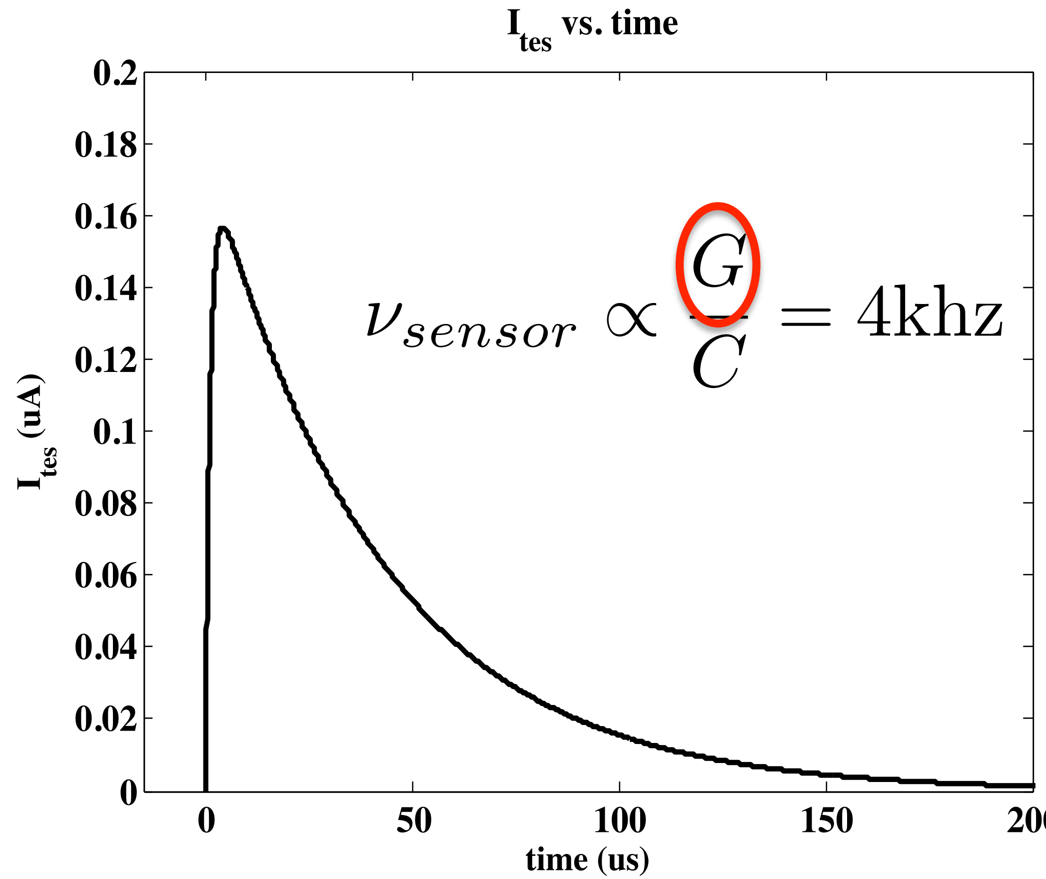


Phonon Signal Bandwidth



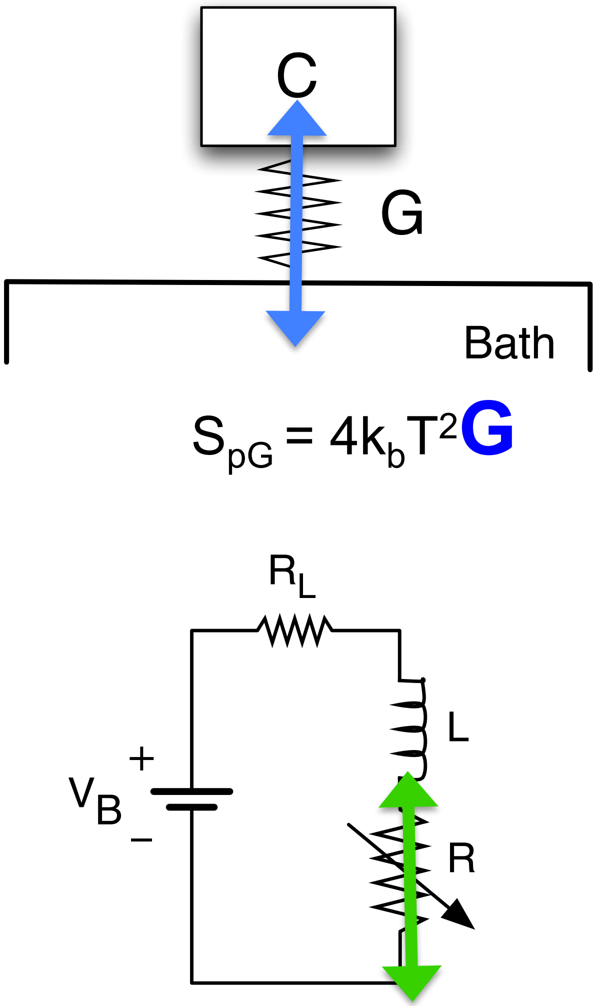
Transition Edge Sensor: Dynamics

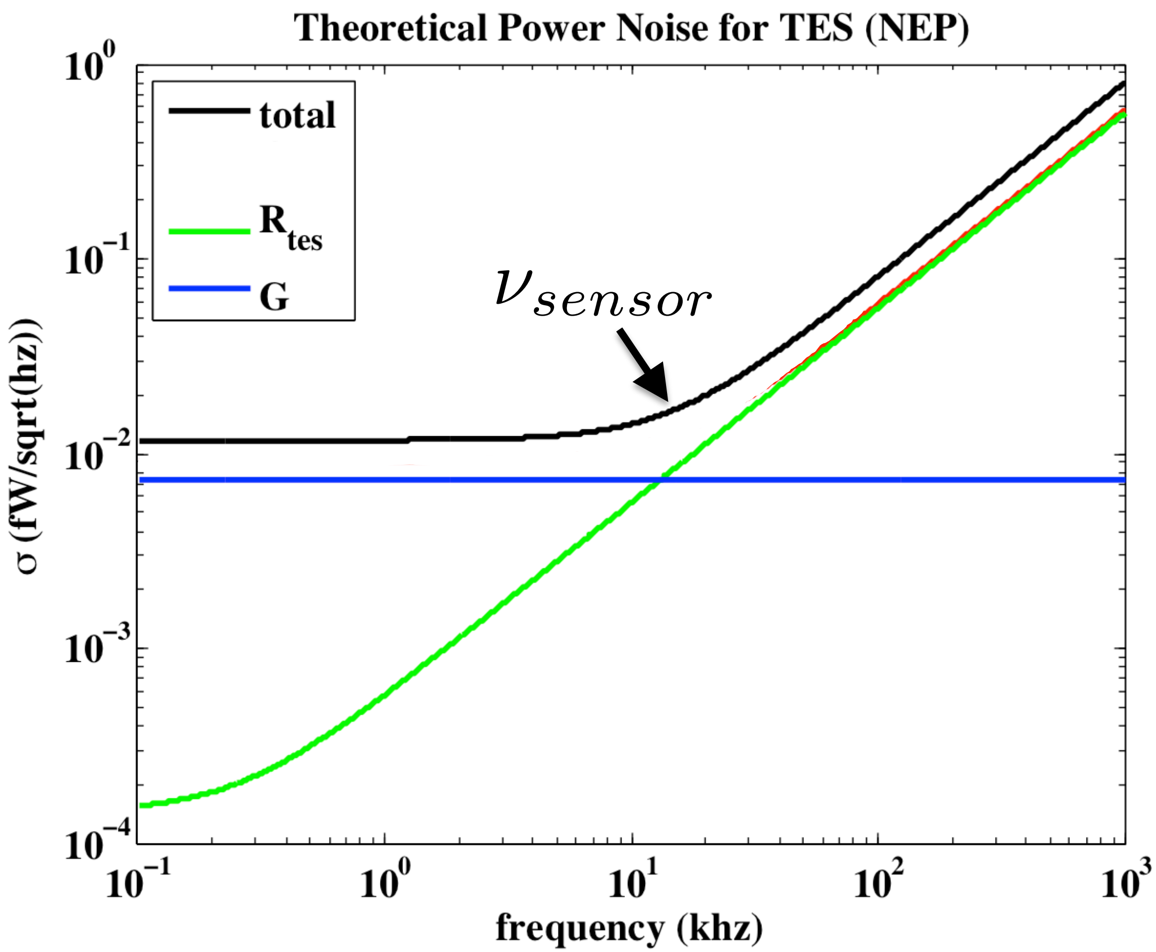




$$\nu_{signal} << \nu_{sensor}$$

Transition Edge Sensor: Noise

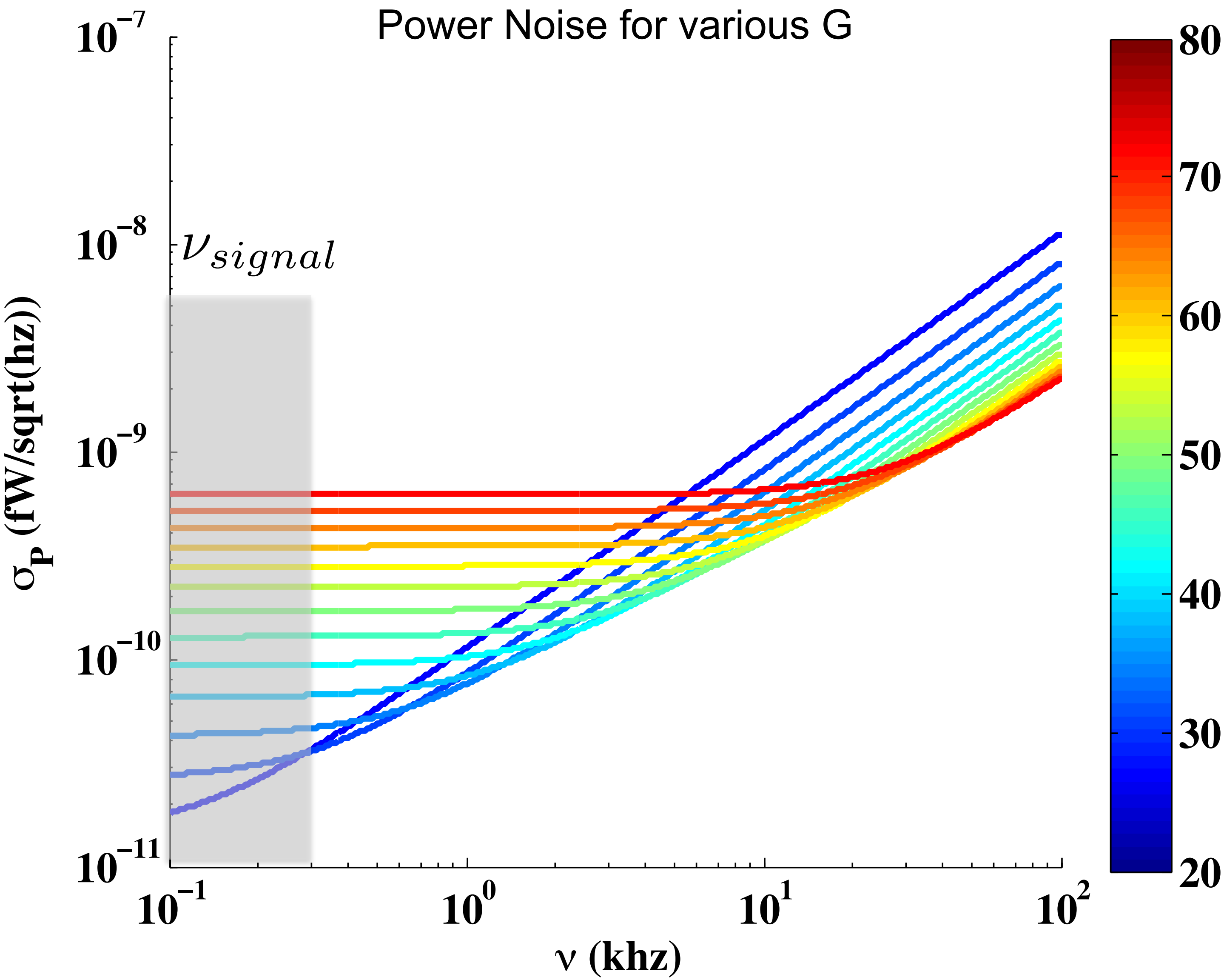




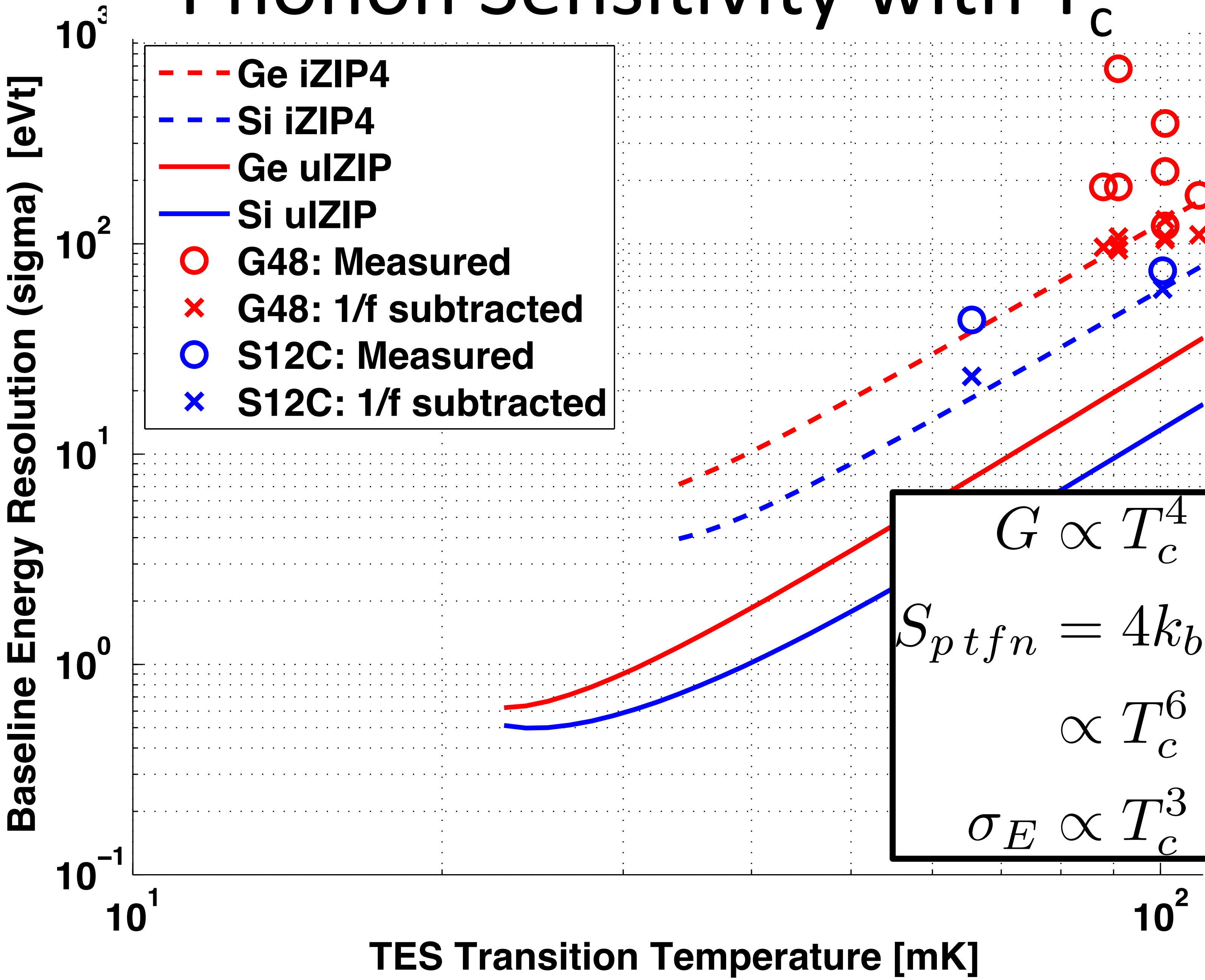
DC noise scales with G

Bandwidth Optimization Rule

$$\nu_{sensor} < \nu_{signal}$$



Phonon Sensitivity with T_c



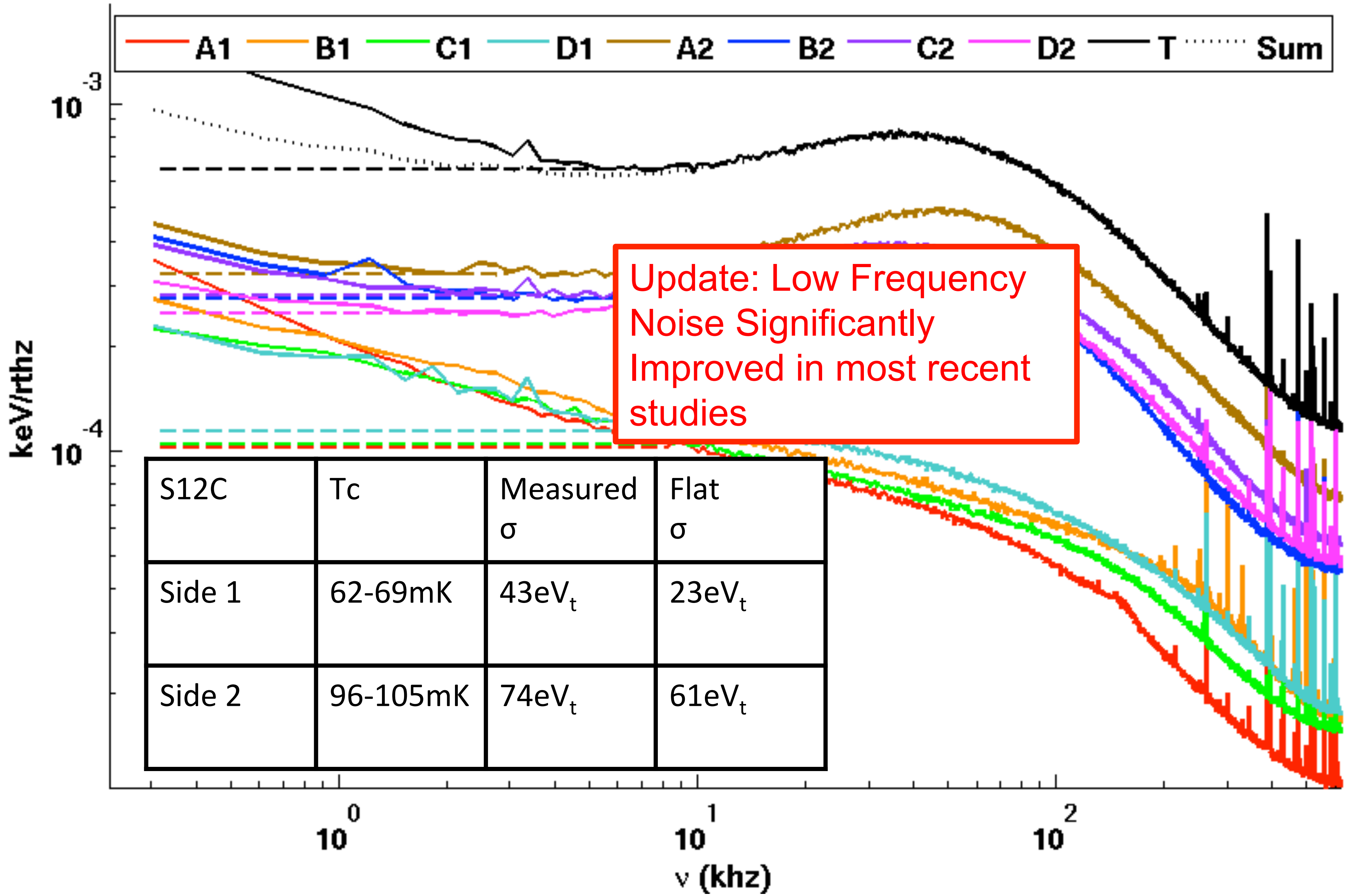
$$G \propto T_c^4$$

$$S_{ptfn} = 4k_b T_c^2 G$$

$$\propto T_c^6$$

$$\sigma_E \propto T_c^3$$

S12C: Our Best Resolution Ever

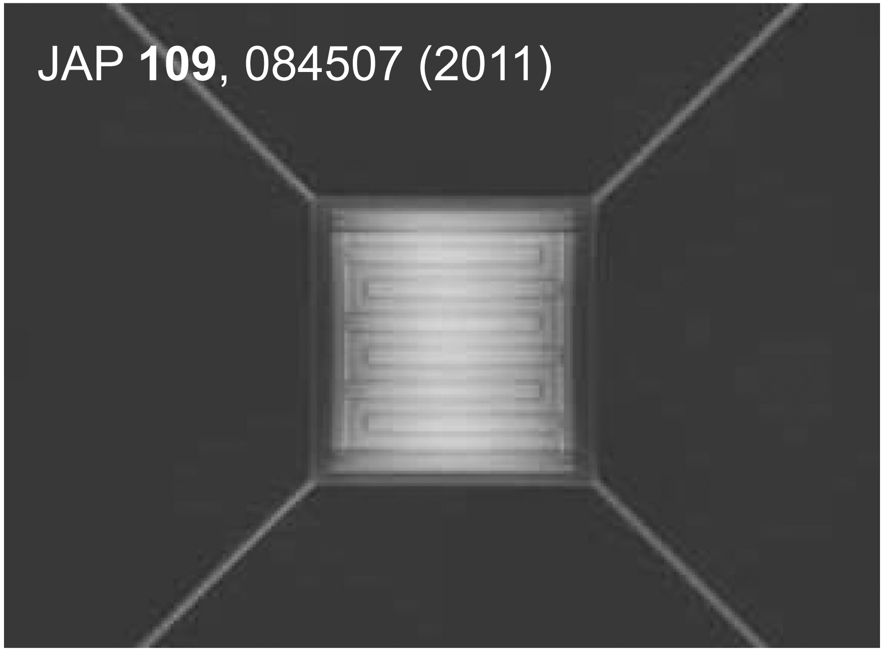


Update: Low Frequency Noise Significantly Improved in most recent studies

S12C	Tc	Measured σ	Flat σ
Side 1	62-69mK	$43eV_t$	$23eV_t$
Side 2	96-105mK	$74eV_t$	$61eV_t$

Potential Problems: Parasitic Power

- Parasitic Power Noise
  - **Vibrations**
  - High Frequency EMI
  - IR



	SuperCDMS (modeled)	SAFARI (measured)
Tc	30 mK	111 mK
G	12800 fW/K	170 fW/K
P_{bias}	76 fW	8.9 fW
S_{NEP}	6×10^{-19} W/rthz	4.2×10^{-19} W/ rthz

SAFARI has created devices with x75 smaller G & x9 smaller P_{bias} than we require

Nuclear Recoil Ionization #1

- Ionization Yield for 254eVr nuclear recoil directly measured via $^{72}Ge(n,\gamma)$
- K.W. Jones and H.W. Kramer PRA 11 (1975)

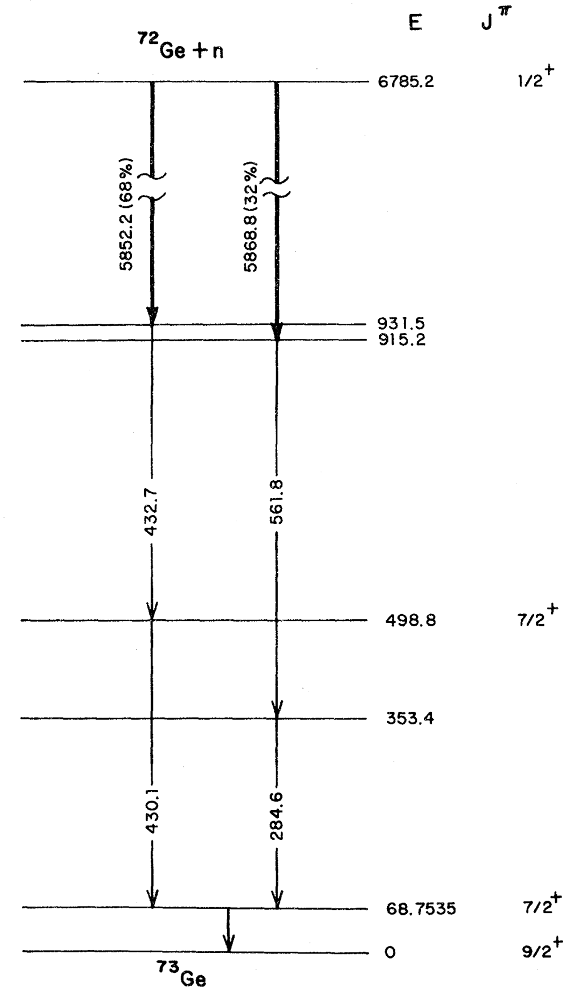
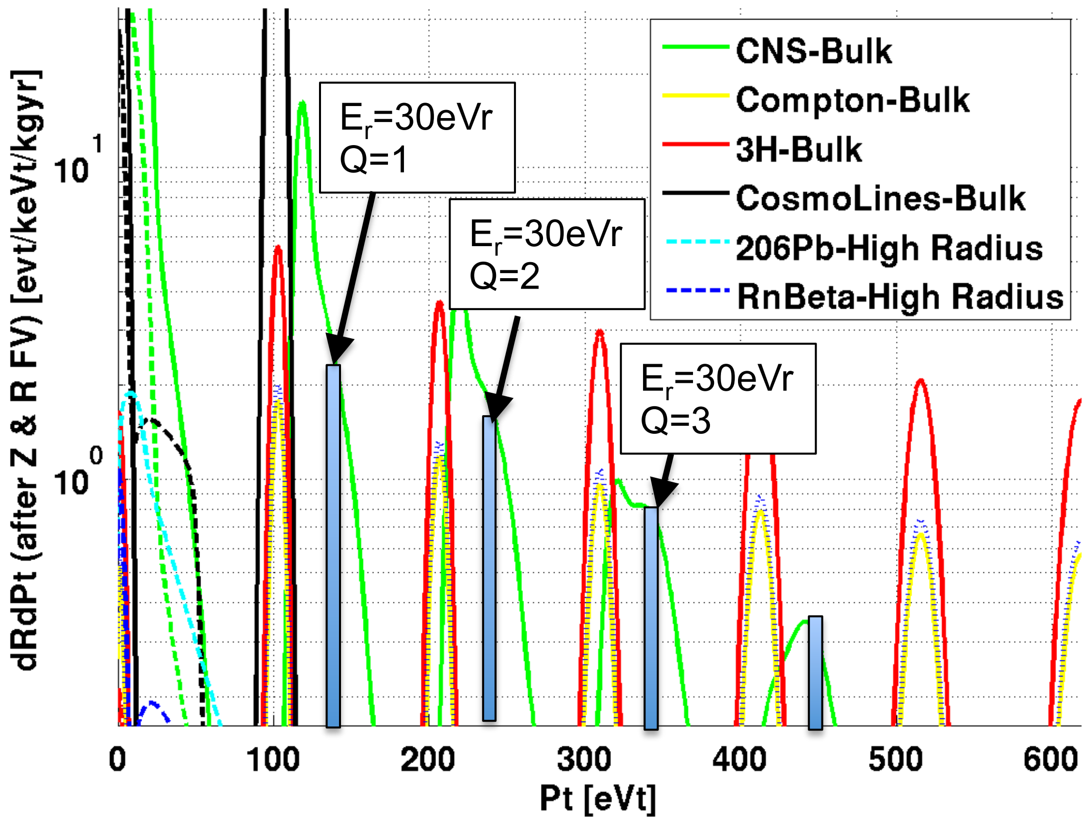


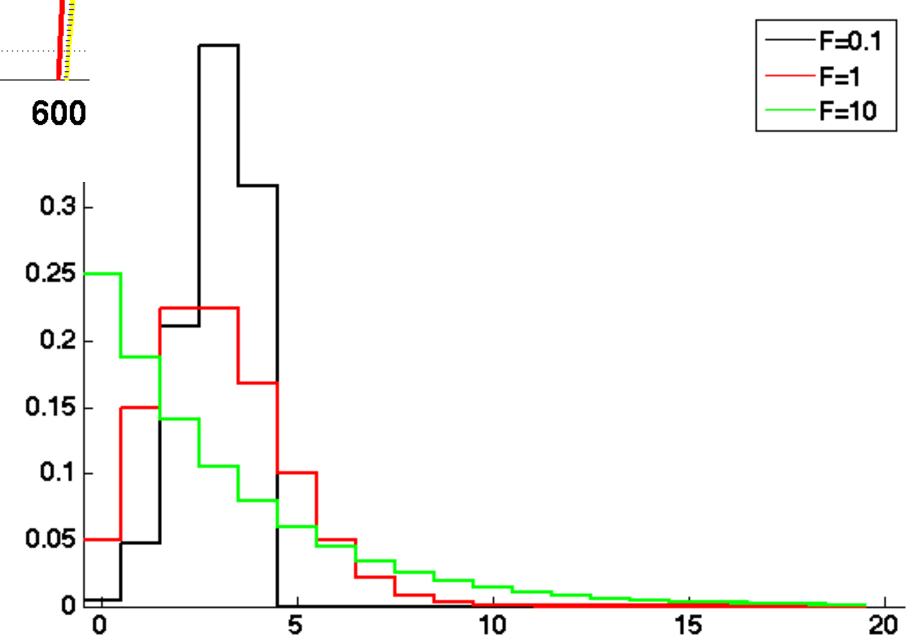
FIG. 1. Simplified decay scheme for the $^{72}Ge(n,\gamma)^{73}Ge$ reaction. Only the decays of levels between 0 and 2-MeV excitation which populate the 68.75-keV excited state and which are also fed by primary capture γ rays are shown. Data from Ref. 8–12 are summarized here.

Nuclear Recoil Ionization #2



SuperCDMS HV can directly measure the full ionization pdf as a function of energy

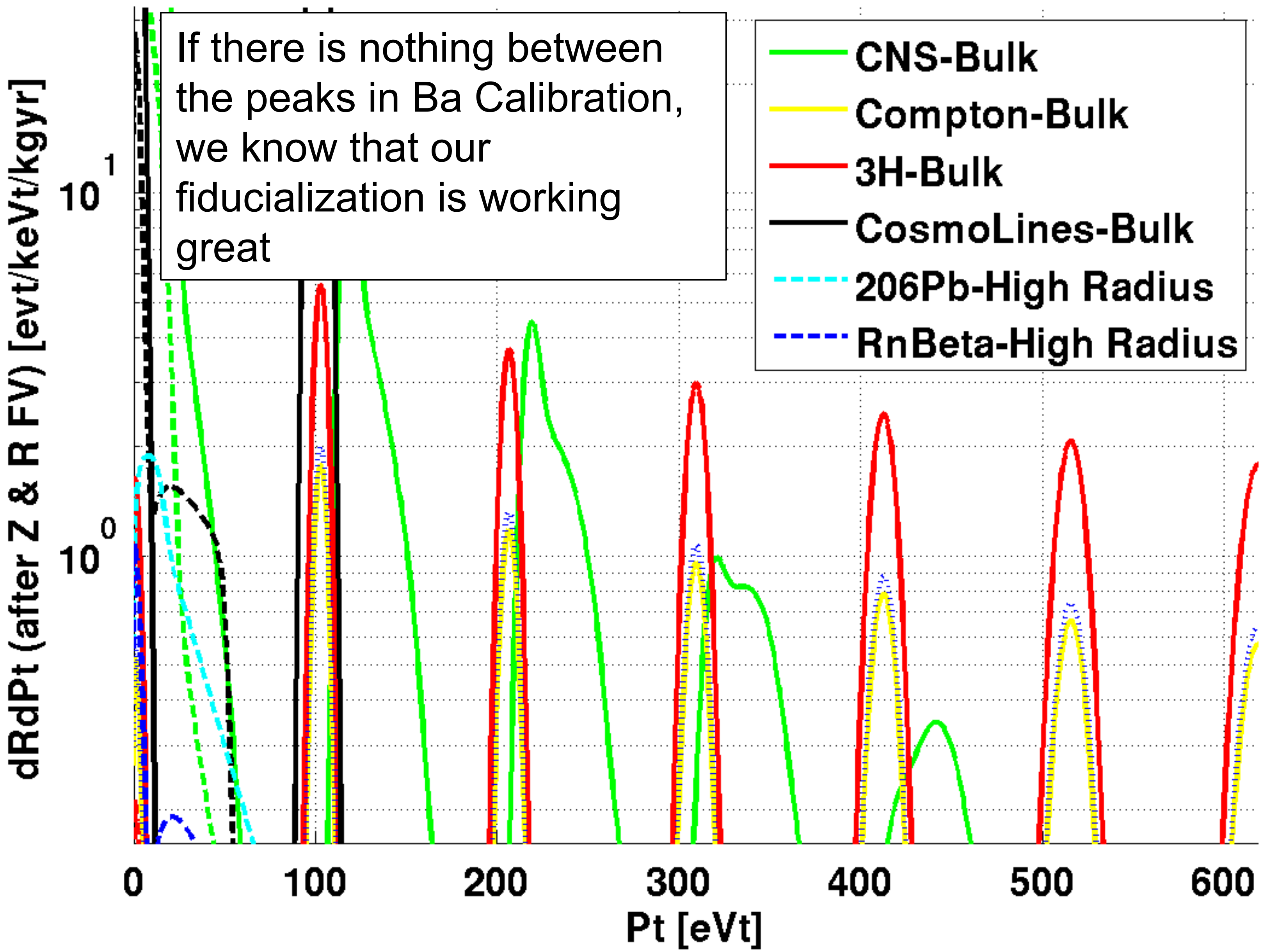
Discrete Ionization Distributions



Systematics:

- Degenarcies between Pt(Er,Q)
- Multiple Scatters

Fiducialization



NaI Calorimeters

- P. Nadeau et al (Philippe) 1410.1573
- Orbital Coupling
- ER/NR Discrimination (CRESST like)