# Light Dark Matter

## Theoretical Motivation
## Detection Techniques

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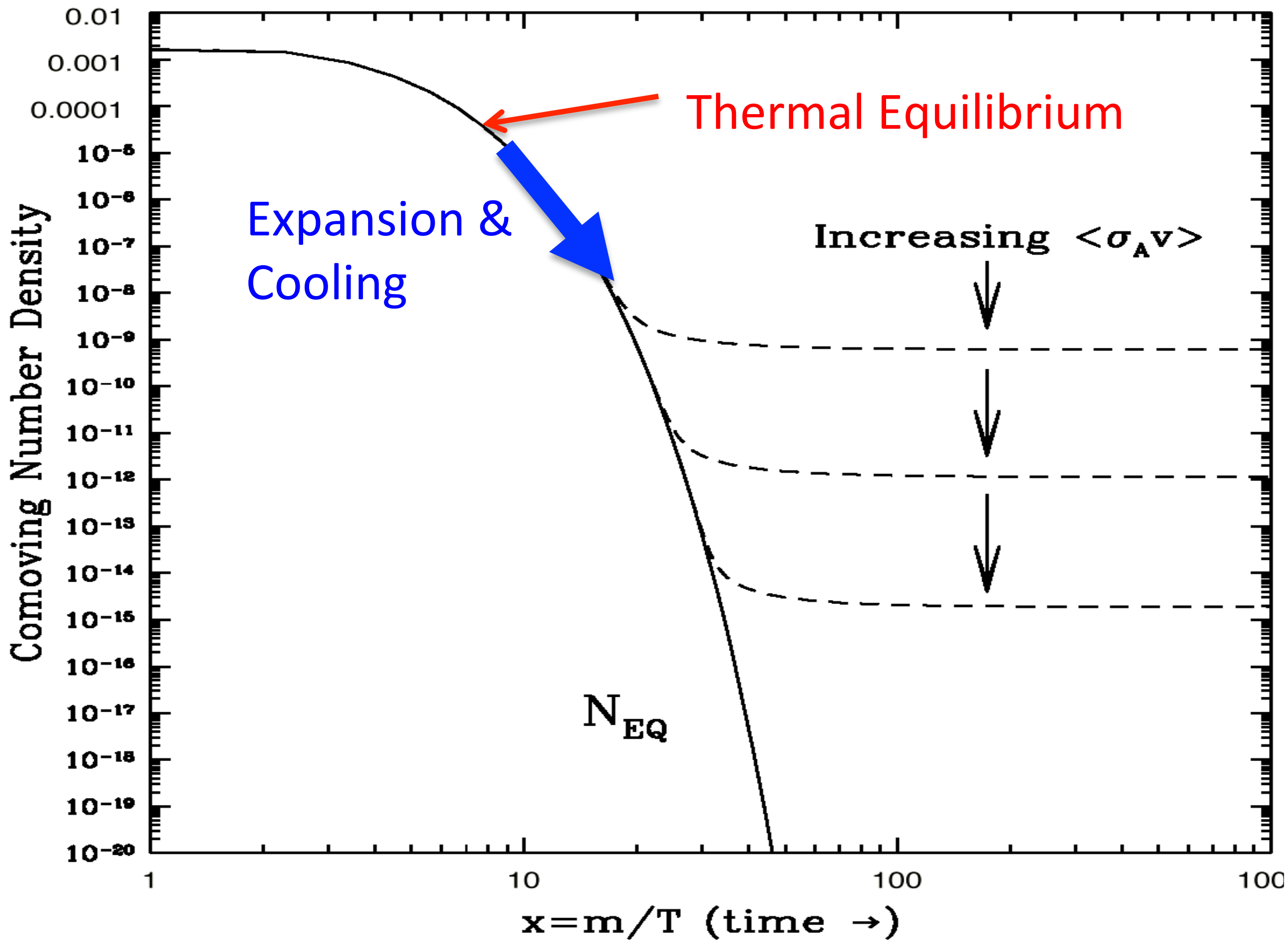
1/10/2013 Argonne: CPAD Instrumentation

# The WIMP Narrative

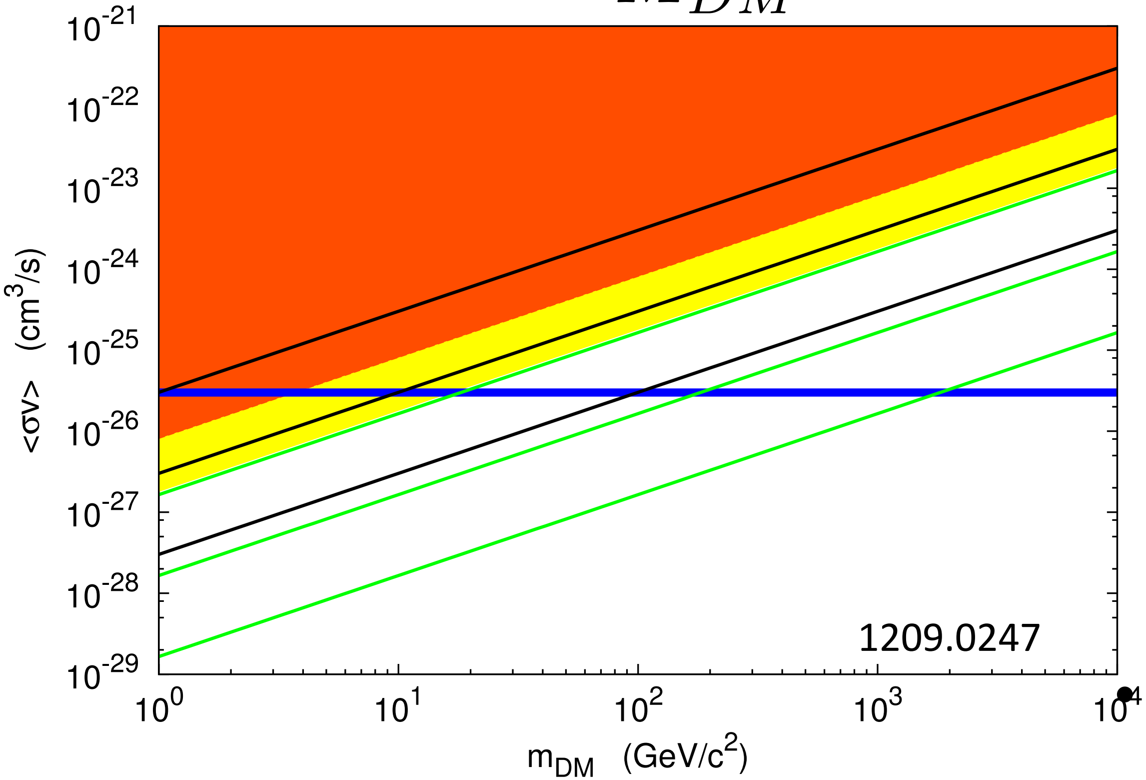



- Dark Matter Relic Density consistent with weak scale ($M_{w,}$ $\sigma_w$)
- Hierarchy Problem: We expect new physics /new particles at weak scale

# CMB Exclusion Region

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

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



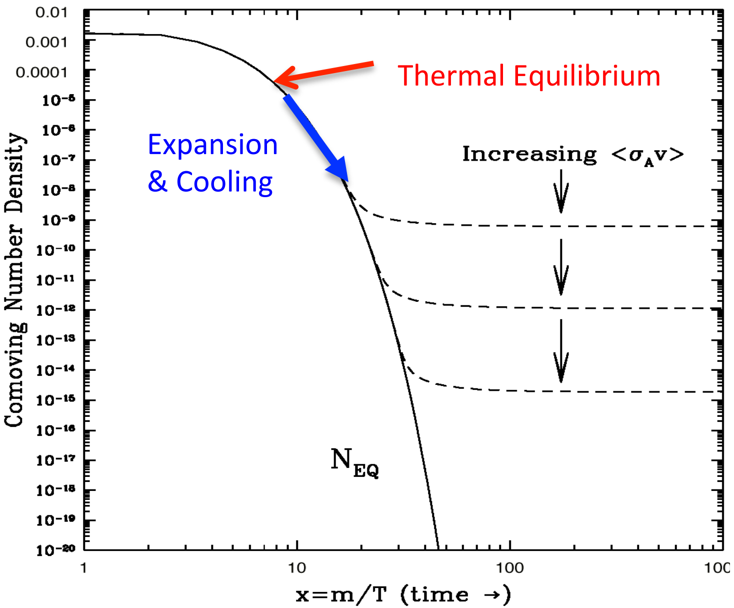

- Energy Injection During Recombination
  - delays photon decoupling
- Energy Injection after recombination increases optical depth
  - more ionized particles = more scatter
  - Limits stronger if structure dependence taken into account
    - G. Giessen et al
    - 1209.0247
- WMAP7 + SPT

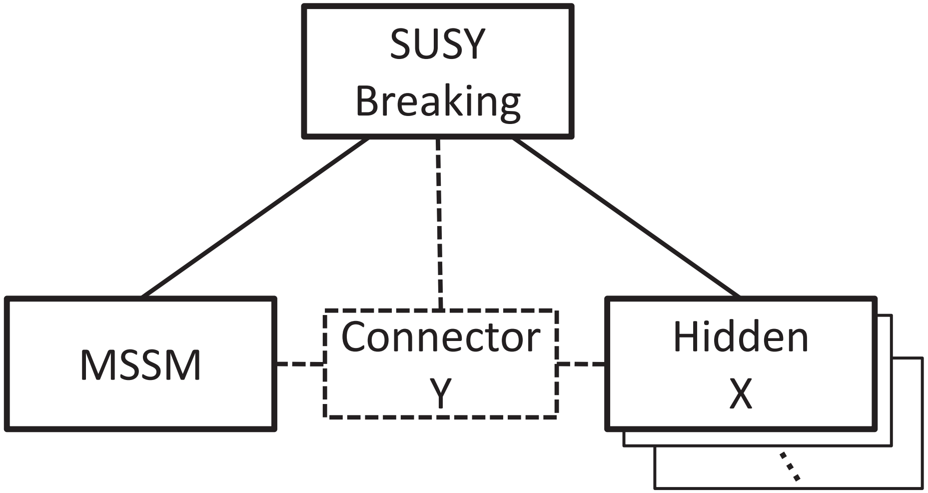
$M_{WIMP} > 10GeV$

Planck: $M_{WIMP} > 100GeV$

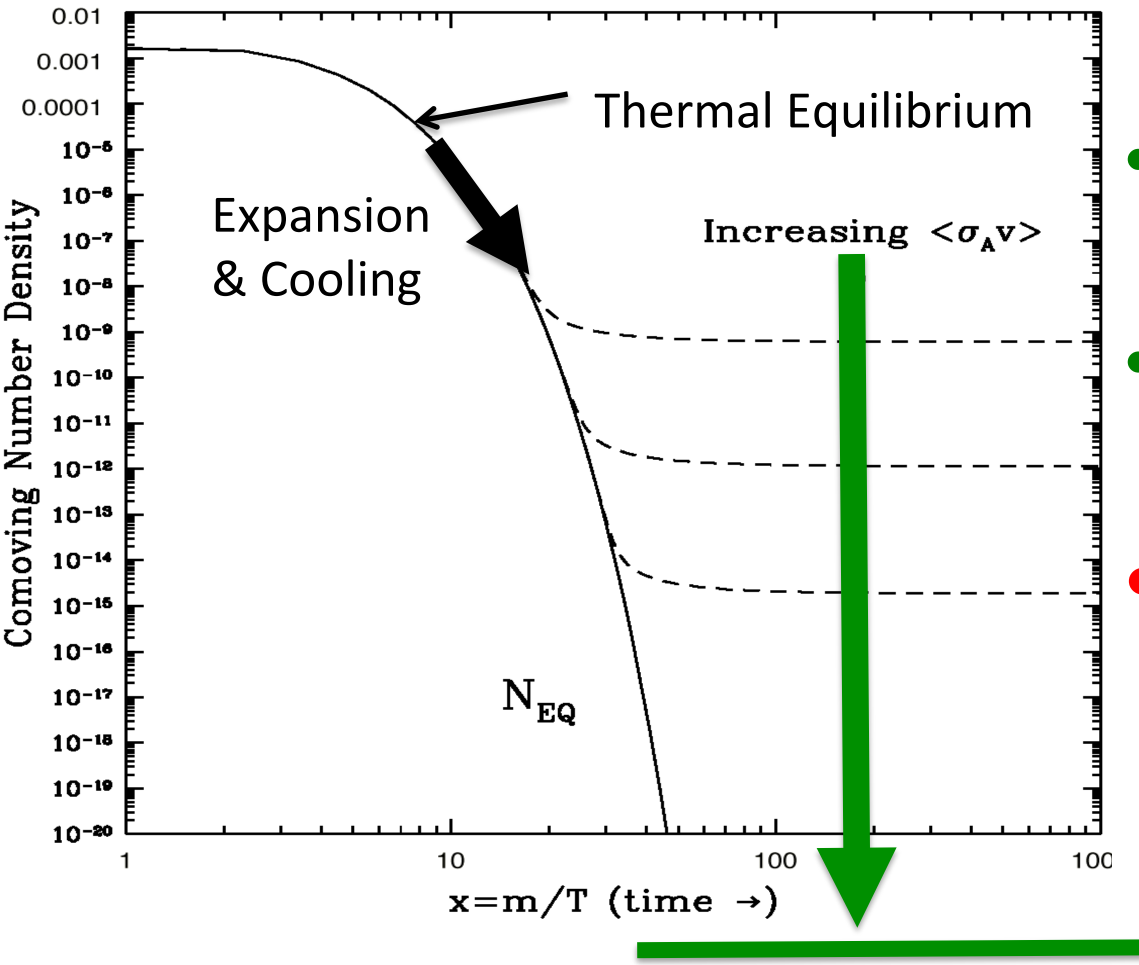
# 1) Hidden Sector Freeze-Out

- Thermal Freeze Out
- Annihilation Energy -> Dark Sector
- $$\Omega_{DM} \propto \frac{1}{<\sigma v>} \sim \frac{m_{DM}^2}{g_{DM}^4} \sim \frac{m_W^2}{g_W^4}$$ WIMP Miracle remains intact!
- Feng & Kumar
  – 0803.4196
- Pretty Natural!



# WIMP Story -> Baryons




- Large Interaction Cross Section
- Incredibly small relic density
- WE DON'T EXIST

What's missing?

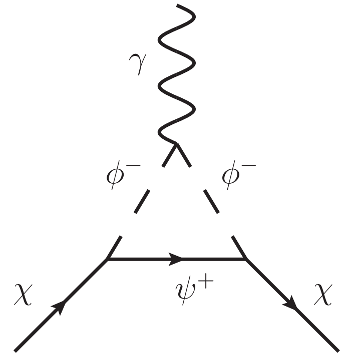
Baryon-AntiBaryon Assymetry

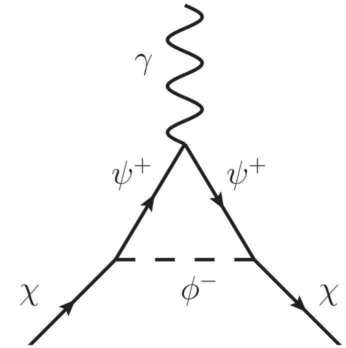
# 2) Asymmetric Dark Matter

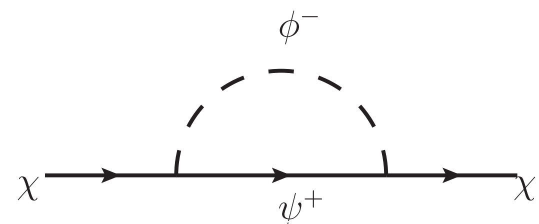
- Kaplan et al
  - 0901.4117
  - Rooted in Technicolor
- Relic Density Determined by Asymmetry Magnitude (NOT Freeze Out)
- No Power Injection at low Z-> No distortion of CMB
- "ADM Miracle"
  - $\Omega_{DM} \sim 5\ \Omega_B$ -> $M_{DM} \sim 5\ M_B$
  - $M_{DM}$ ~5GeV

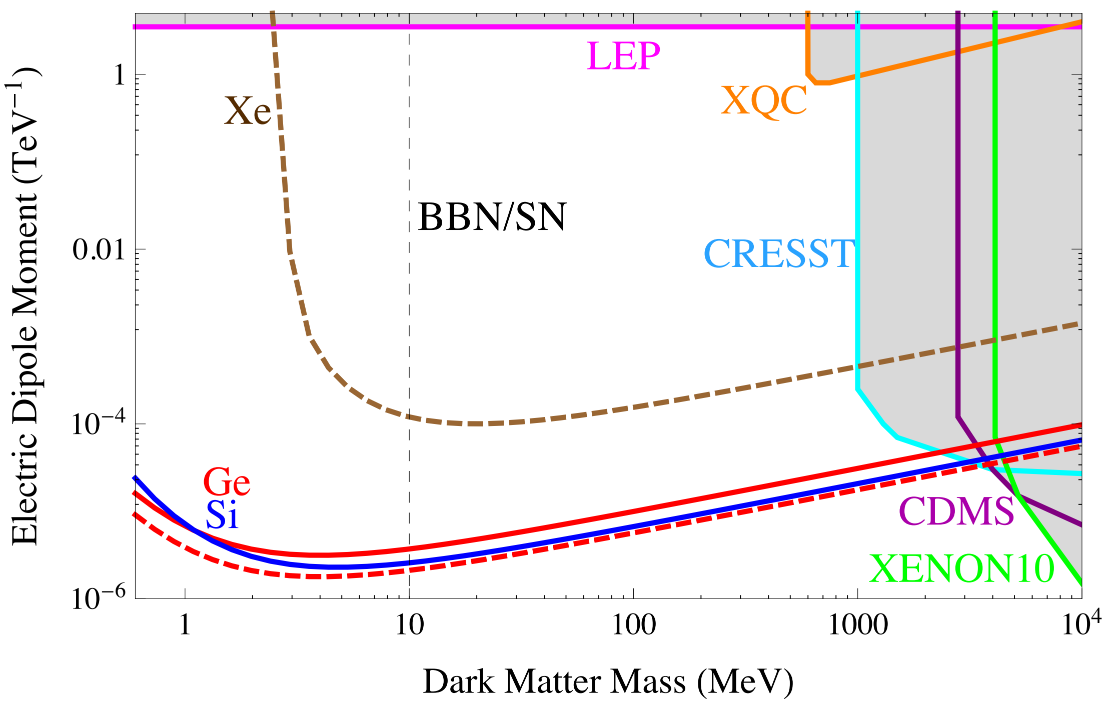
# Ex: Electric/Magnetic Dipole Coupling DM

- ADM
- P. Graham et al
  - 1203.2531
- Not Excluded by LEP/LHC



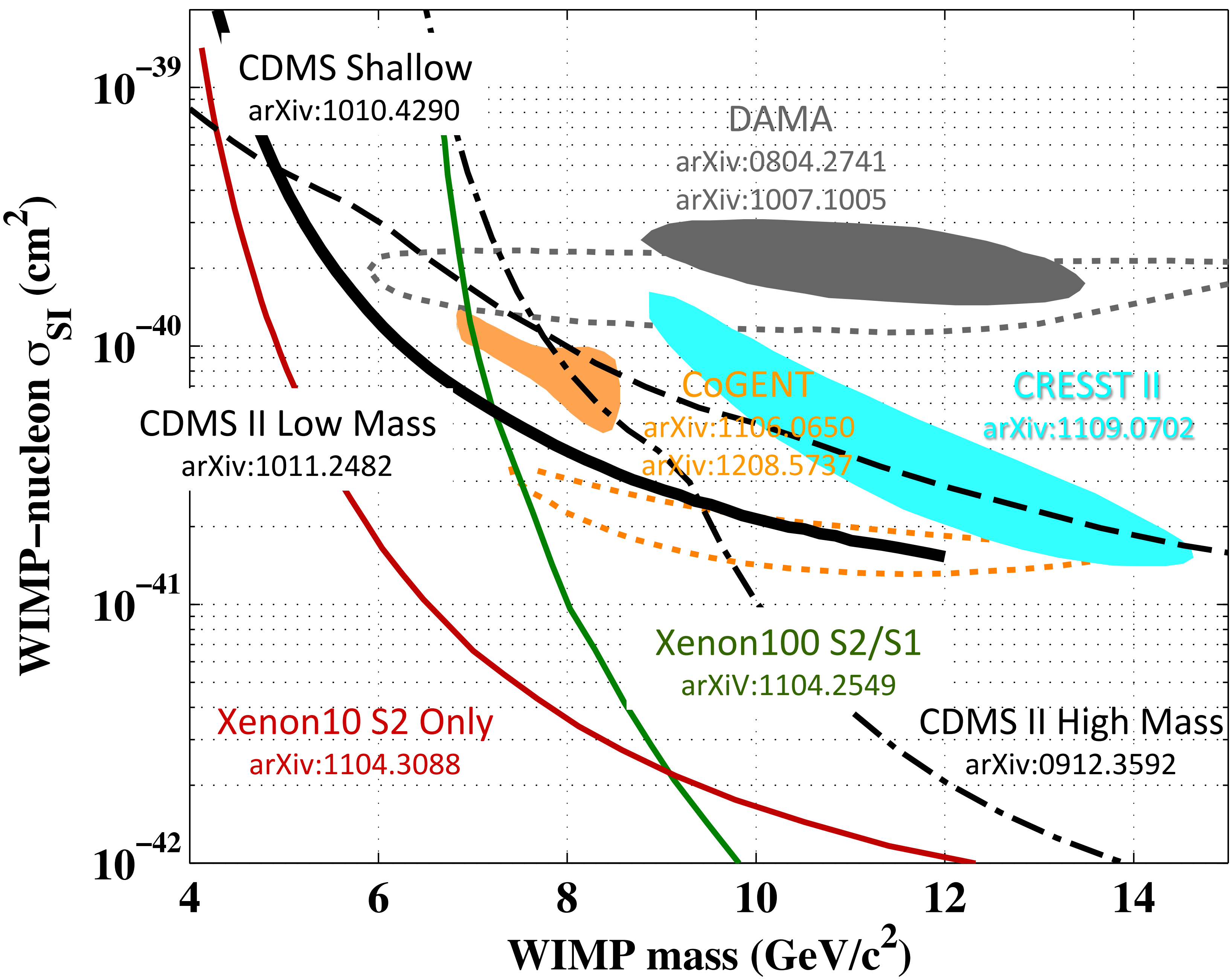



# Summary: Theoretical Motivation

- Standard Thermal Freeze WIMP Miracle is Definitely Well Motivated
- Many “Natural” Theories still have Dark Matter Candidates with 1MeV $<M_{DM}<$10GeV
  1. Hidden Sector Freeze Out
  2. Asymmetric Dark Matter
  3. Freeze In Dark Matter (L. Hall et al 0911.1120)
- How do we allocate resources?

# Experimental Motivation

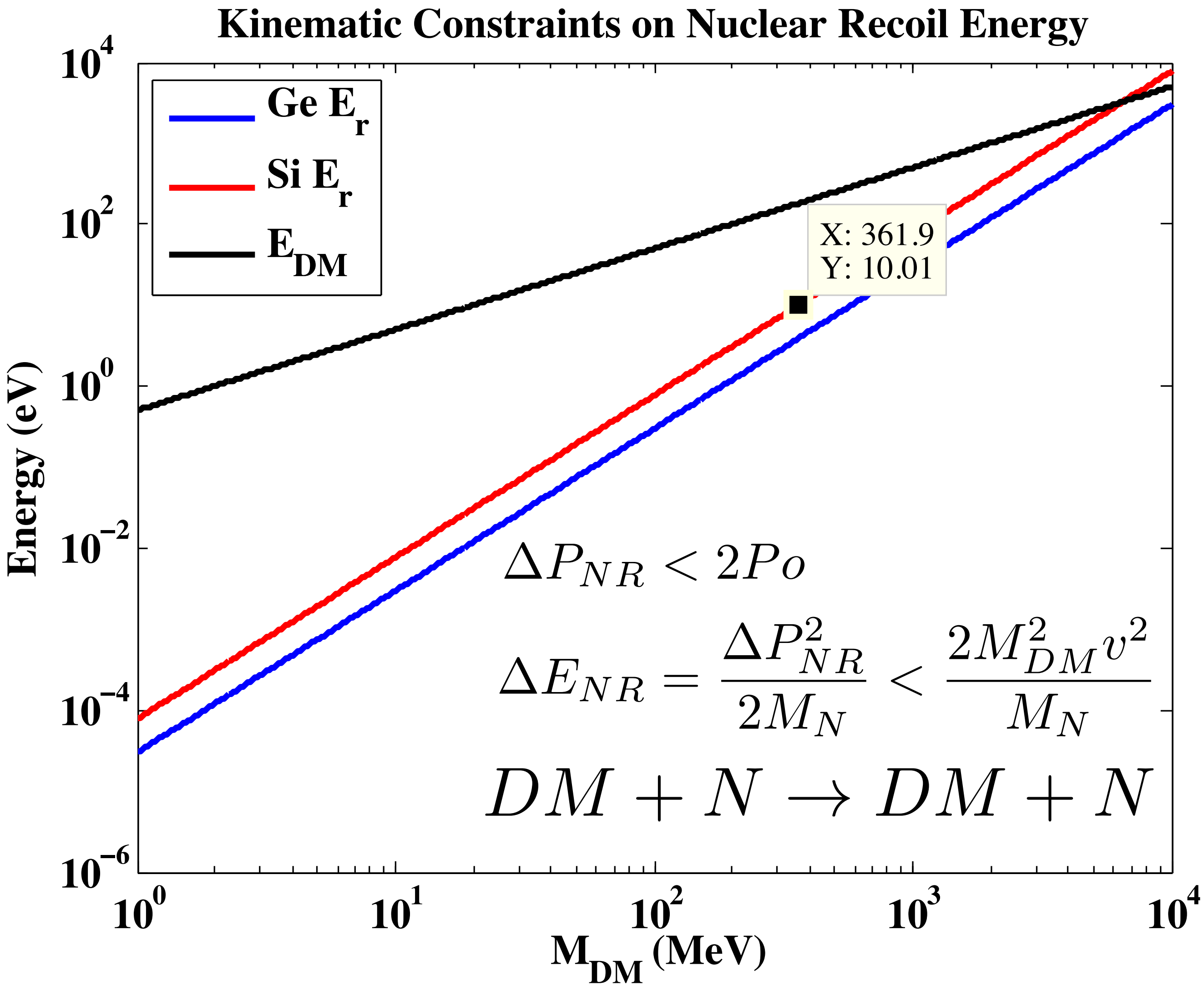


# Experimental Motivation

- Near Threshold Signal Excesses Could Be First Hints of Dark Matter
  - MDM ~ 5GeV: Asymmetric Dark Matter Miracle
- Systematics are Hard to Control Near Signal Threshold
  - DAMA -> trigger efficiencies?
  - CRESST -> Sputtering from $^{210}$Pb decays at low energies
  - CoGENT -> Surface Event Leakage Efficiency

IMPROVE DETECTOR SENSITIVITY

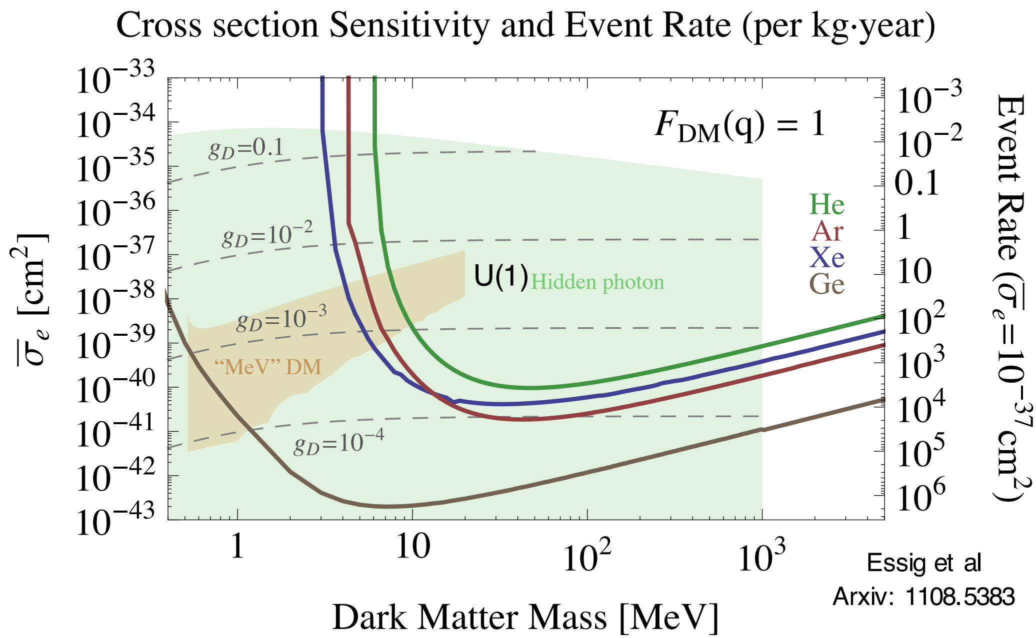
# Experimental Techniques: 1MeV<M$_{DM}$<1GeV



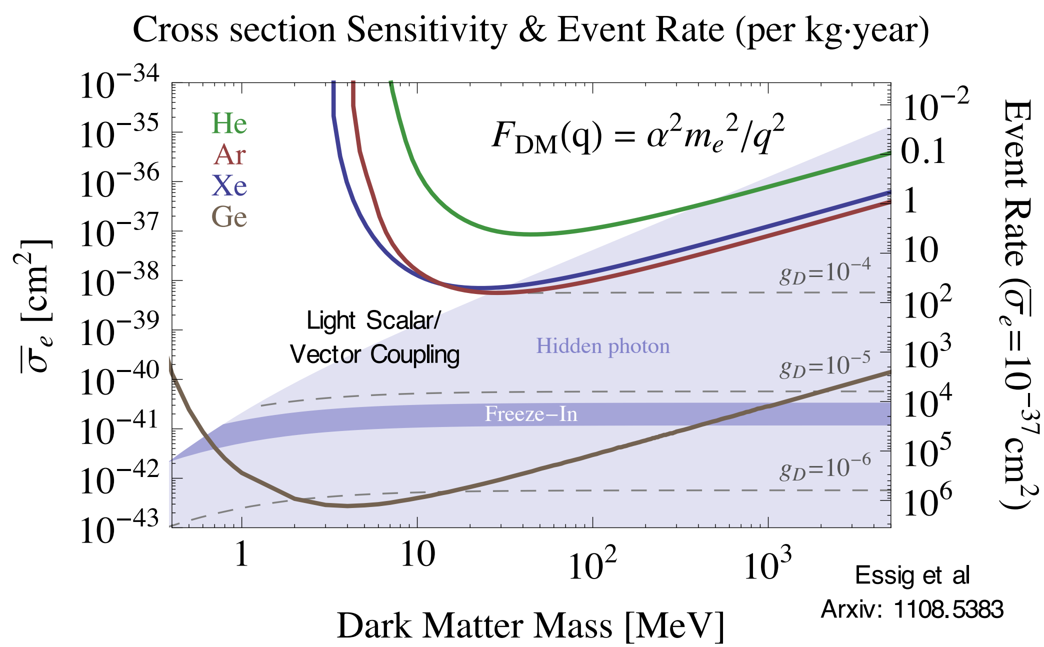

- Essig et al. Arxiv: 1108.5383
- $DM + e^- \rightarrow DM + e^-$

# Experimental Techniques: 1MeV<$M_{DM}$<1GeV

- Ideally Requires Single $e^-/h^+$ pair sensitivity
- Ge & Si >> Ar, Xe, & He because of small bandgap
- Compton Background Less Important
- Essig et al
  - arXiv: 1108.5383

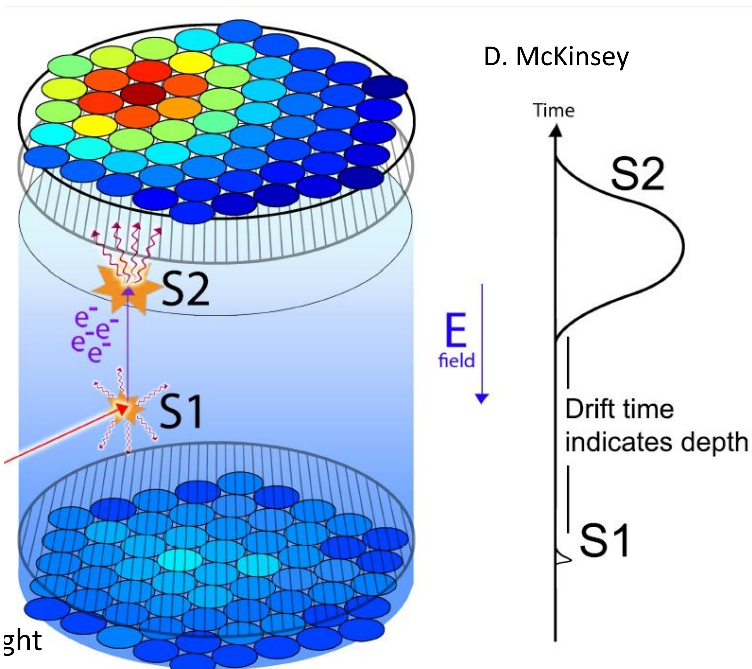



Essig et al
Arxiv: 1108.5383

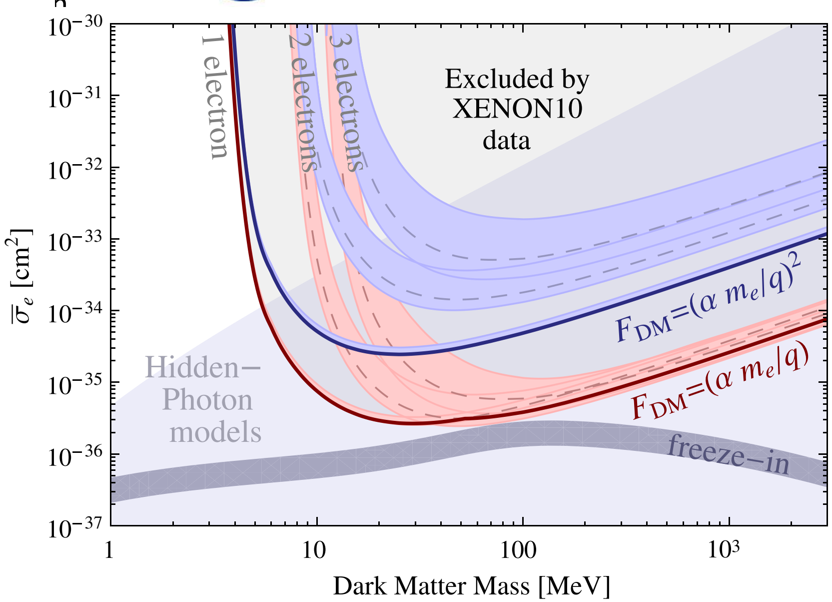


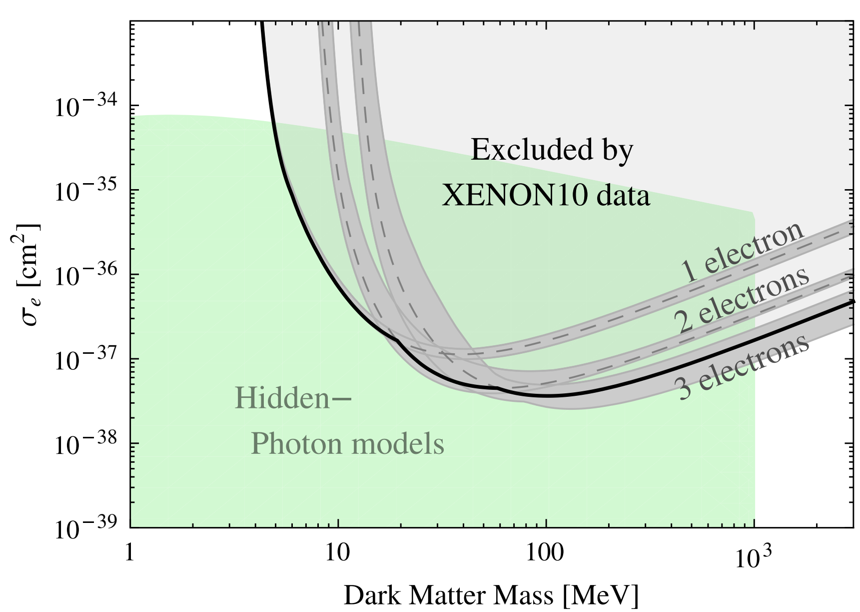

Essig et al
Arxiv: 1108.5383

# Measuring Single Excitations: Noble Gas TPCs




- S2 Only Xenon10
- Essig et al
  - PRL 109 021301 (2012)
- S2 Detector Background Rates
  - $1e^-$ = 23.4 evt/kgd
  - $2e^-$ = 4.2 evt/kgd
  - $3e^-$ = 0.9 evt/kgd
- **Causal Mechanism?**
- **Mitigation Strategies?**

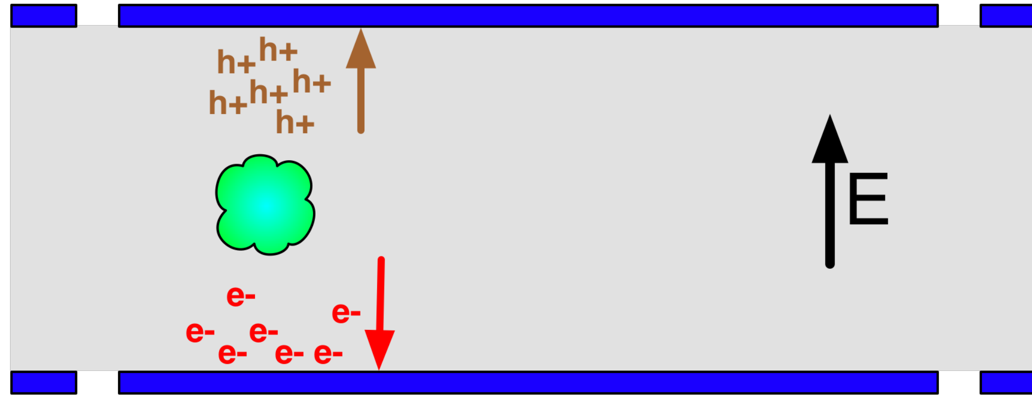


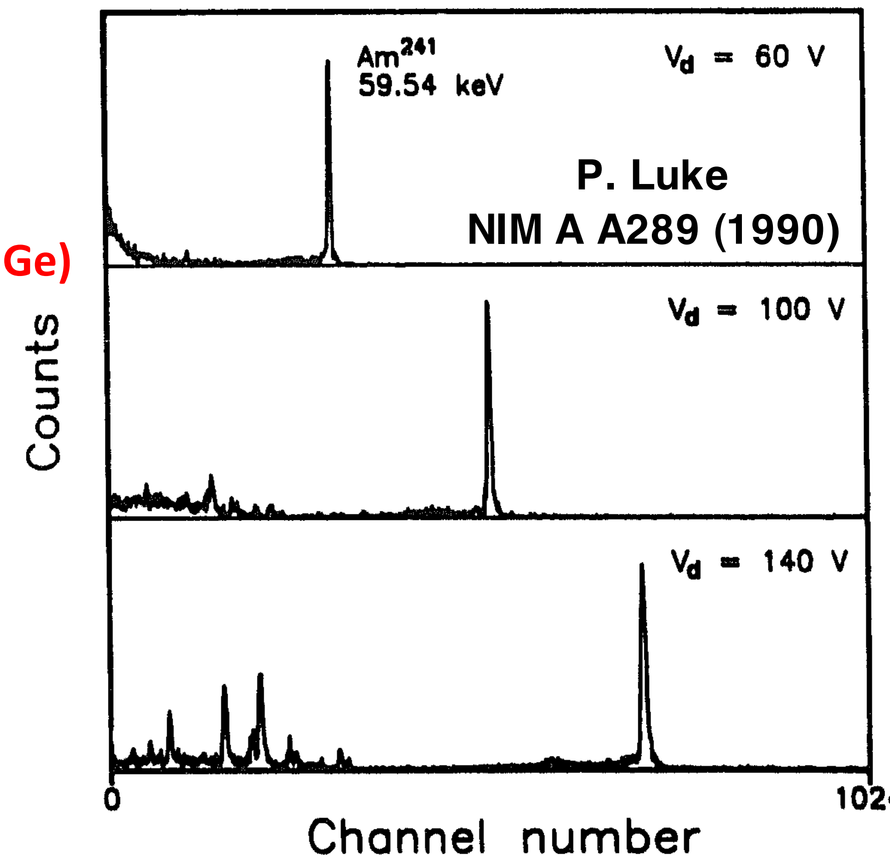
# Measuring Single $e^-/h^+$: Semiconductors

- Luke-Neganov Gain

$$
\begin{aligned}
E_{tot} &= E_r + E_{luke} \\
&= E_r + n_{eh} e V_b \\
&= E_r \left(1 + \frac{eV_b}{\epsilon_{eh}}\right)
\end{aligned}
$$

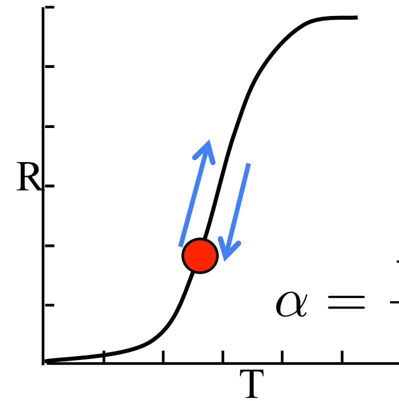



- Current Leakage at high E fields
  - $E_b$ < 25V/cm
  - $V_b$ < 70V for 1" **(best measurement Ge)**
  - Causual Mechanism?
  - Mitigation Strategy
  - Leakage($V_b$)?
- Phonon Sensitivity Requirement:
  - $E_{trigger}$ < 50eV
  - $\sigma_E$ < 9eV

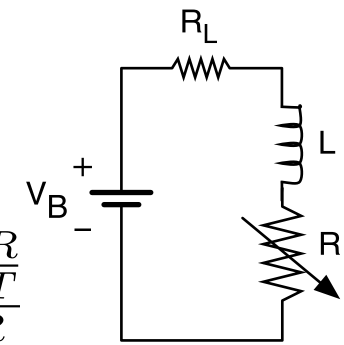


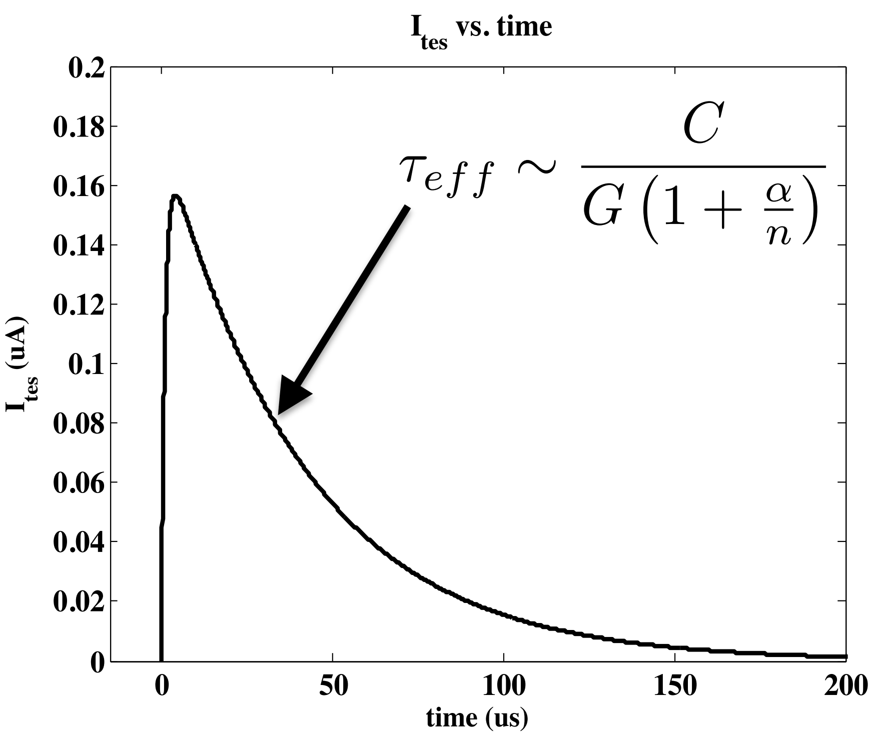
# Transition Edge Sensor

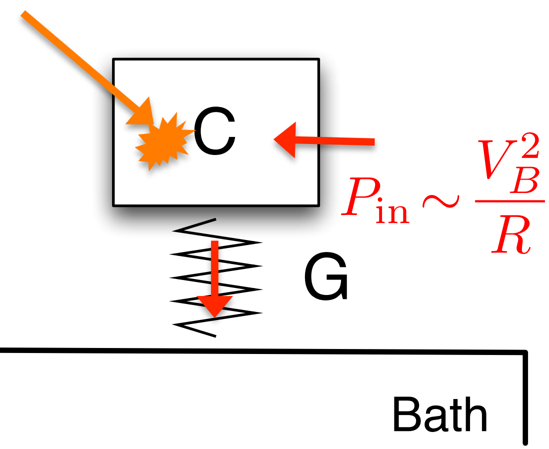
- Superconducting film artificially held within it's transition through voltage biasing
- Resistance incredibly sensitive to temperature change




$$\alpha = \frac{\frac{\partial R}{\partial T}}{\frac{R}{T}}$$



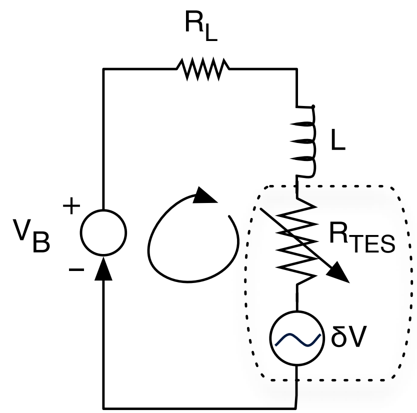



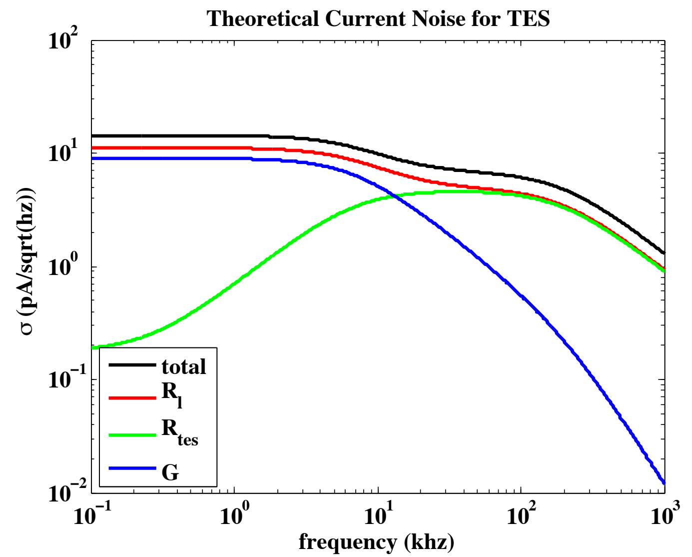




$$\omega_{eff} \propto G$$

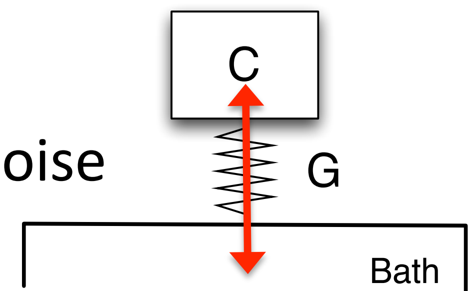
# TES: Intrinsic Noise

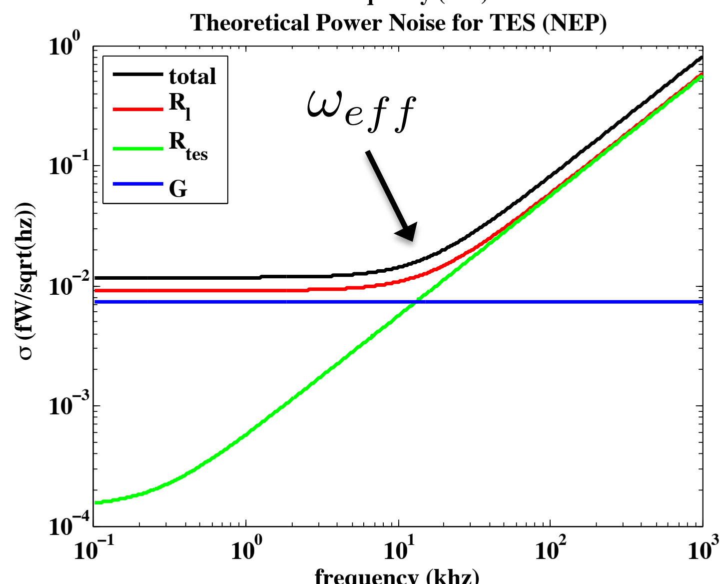
- Johnson Noise
  - $S_{V=}4k_bTR$
  - L/R rolloff
  - $R_{tes}$ feedback suppressed




- Thermal Fluctuation Noise
  - $S_{TFN} = 4k_bT^2G$




$$\omega < \omega_{eff} : S_{NEP} \propto G$$

# Thermal TES Detector Resolution

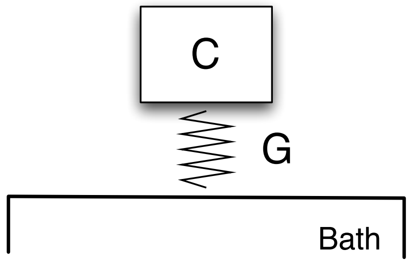
$$\sigma_E^2 = \frac{1}{\int_0^\infty \frac{d\omega}{2\pi} \frac{4|\frac{\partial Q}{\partial E}(\omega)|^2}{S_{NEP}}}$$

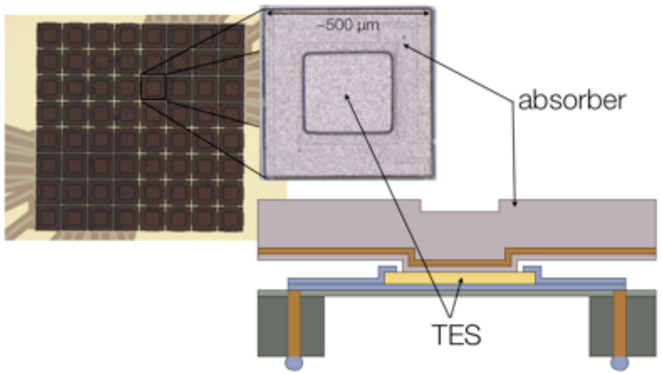
$$\sim \frac{1}{\frac{\Delta\omega}{2\pi} \frac{4}{4k_b T_c^2 G}}$$

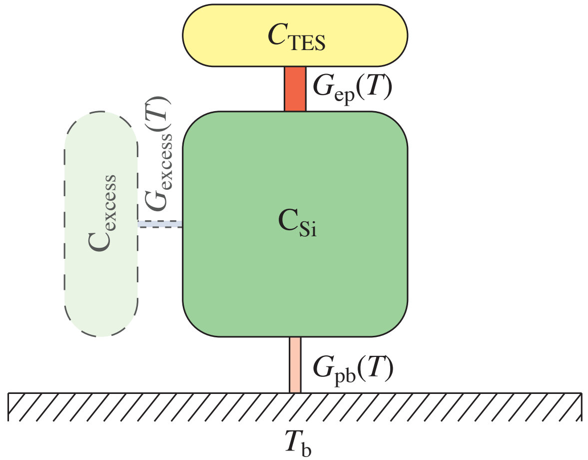
$$\sim \frac{2\pi k_b T_c^2 G}{\Delta\omega}$$

If $\Delta\omega = \omega_{eff} \propto \frac{G}{C}$

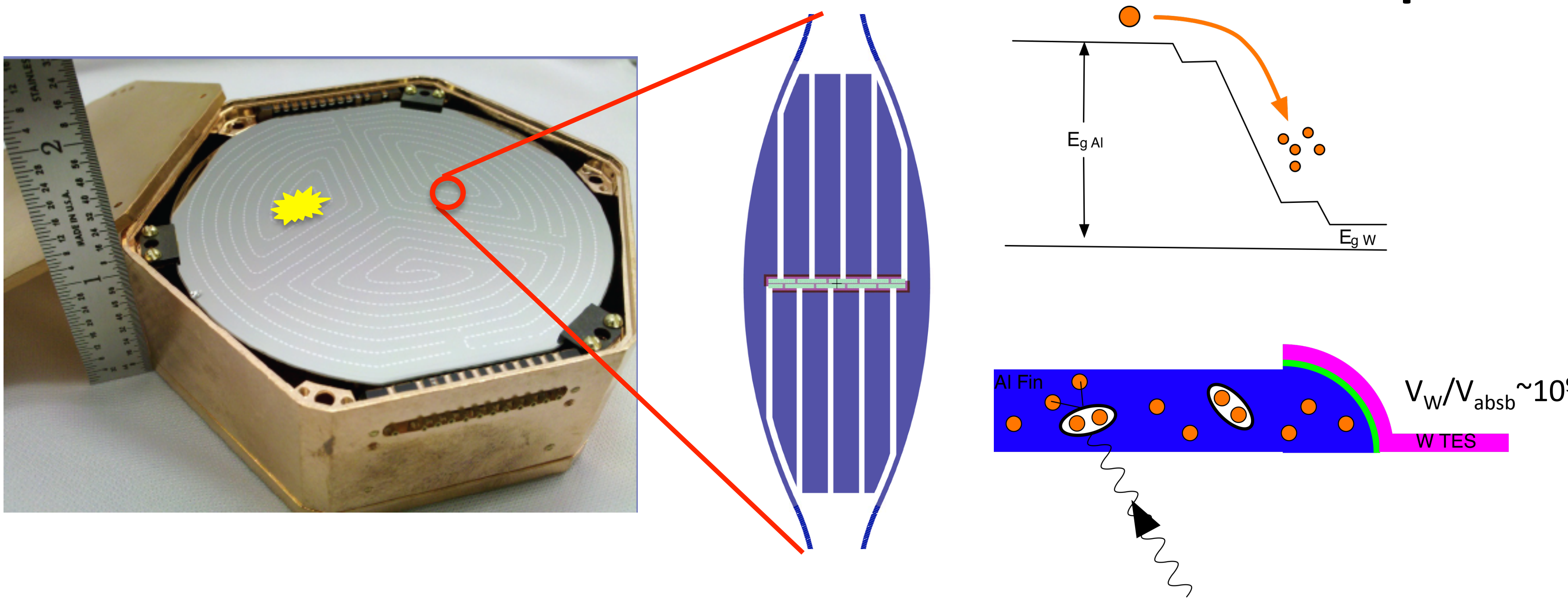
$$\sigma_E^2 = \frac{4k_b(1+\beta)}{\alpha}\sqrt{\frac{F_{tfn} n}{1-\frac{T_{bath}^n}{T_o^n}}} T_c^2 C$$



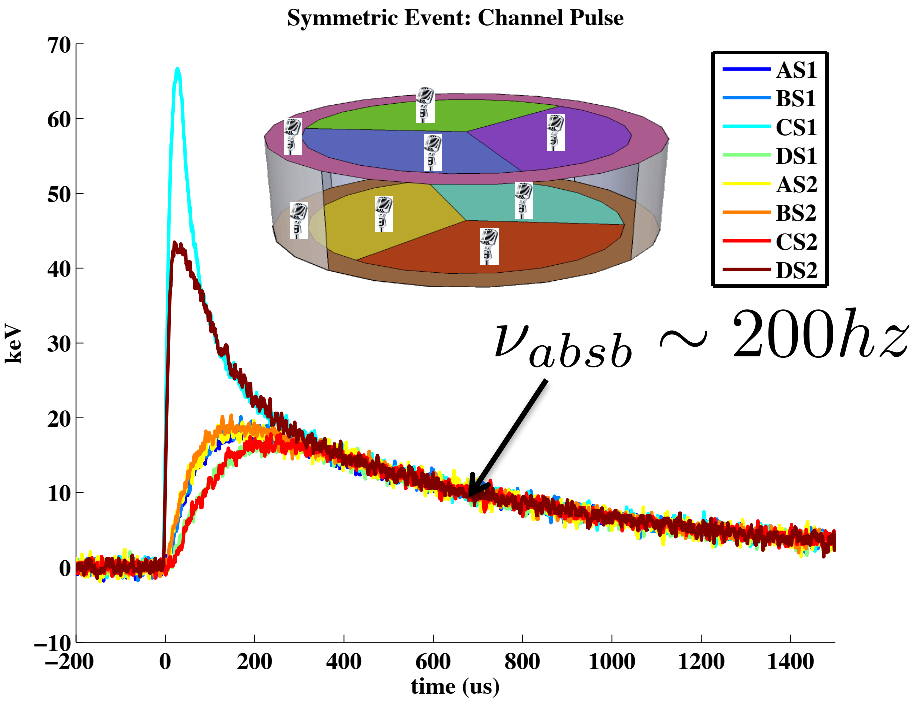



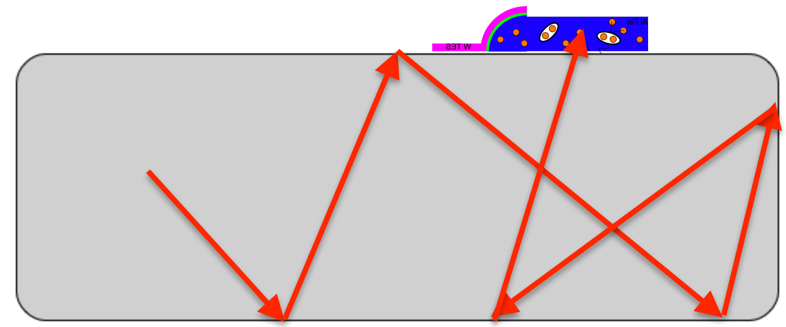
# Athermal Phonon Detection Principles




- Become insensitive to $C_{absorber}$ by collection and concentration of phonons before the thermalize
- More Complex
- Collection efficiencies <ε>: 10-20%

# Athermal Phonon Pulse Shape/Resolution



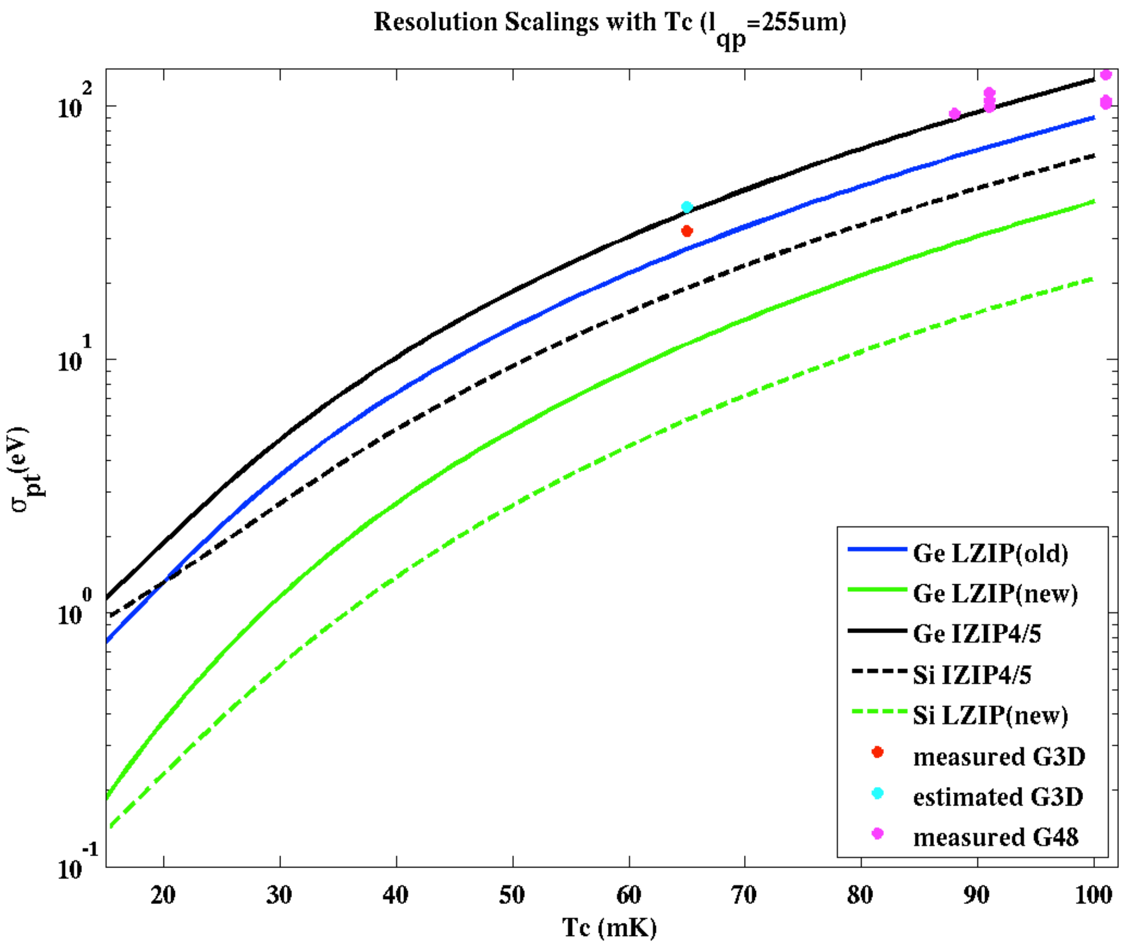



$$\nu_{absb} \propto \frac{N_{QET} A_{Al\,QET} |v_p|}{l_p}$$

- $\nu_{\mathrm{absb}} << \nu_{\mathrm{eff\ phase\ separated}} << \nu_{\mathrm{eff}}$: Bandwidth Mismatch
- $G \propto T_c^4$
- $\sigma^2_{\mathrm{E\,athermal}} = \dfrac{1}{\int_0^\infty \frac{d\omega}{2\pi} \frac{4|\frac{\partial Q}{\partial E}(\omega)|^2}{S_{NEP}}} \sim \dfrac{1}{\nu_{absb} \frac{4}{4k_b T_c^2 G}}$

$$\sigma_{\mathrm{E\,athermal}} \propto T_c^3$$

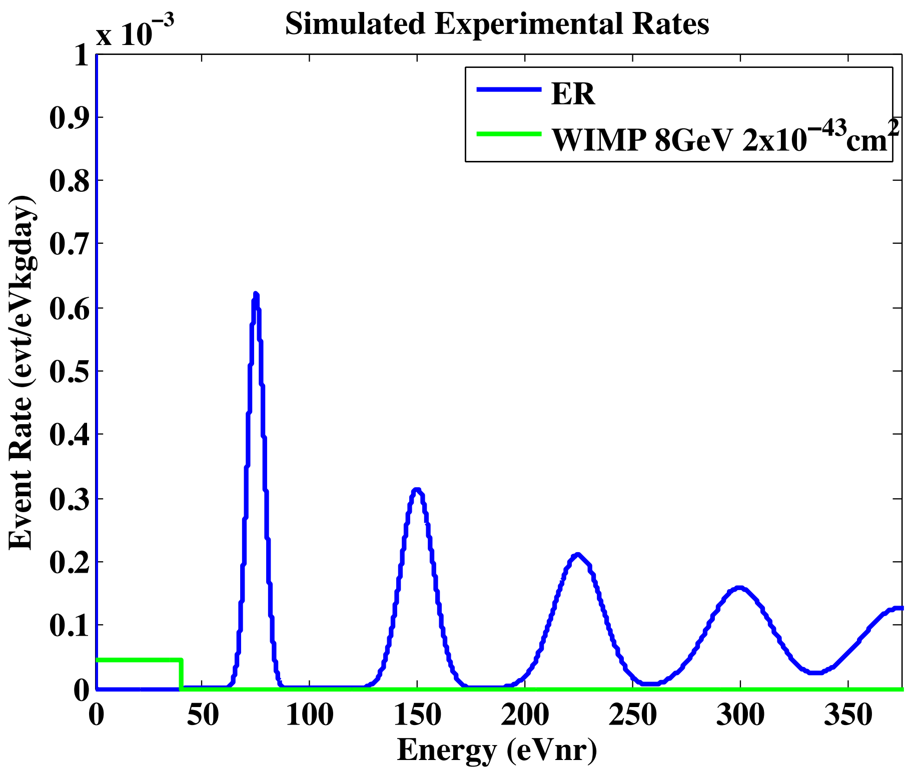
# Athermal Phonon Energy Resolution Estimates




- $\sigma_E \propto T_c^3$
- $T_c$=20mK: x125 better energy resolution than CDMS!
- Engineering Hurdles
  - IR loading
  - 20mK W $T_c$ Possible?

Single Excitation Sensitivity Should Be Possible

# Experimental Techniques 1GeV-10GeV: ER/NR Separation Through Luke Gain




Requirement: <5eV trigger threshold

- Look between e/h peaks for WIMP signal
- Systematically Robust
  - Fiducial Volume Problems lead to ER leakage: Vary $V_b$
  - Crystal Cracking Events (CRESST): look for NR tail on 1$^{st}$ ionization peak
- Discovery Experiment
- ER Background Subtraction possible at higher energies by running at multiple $V_b$
  - arXiv: 1201.3685

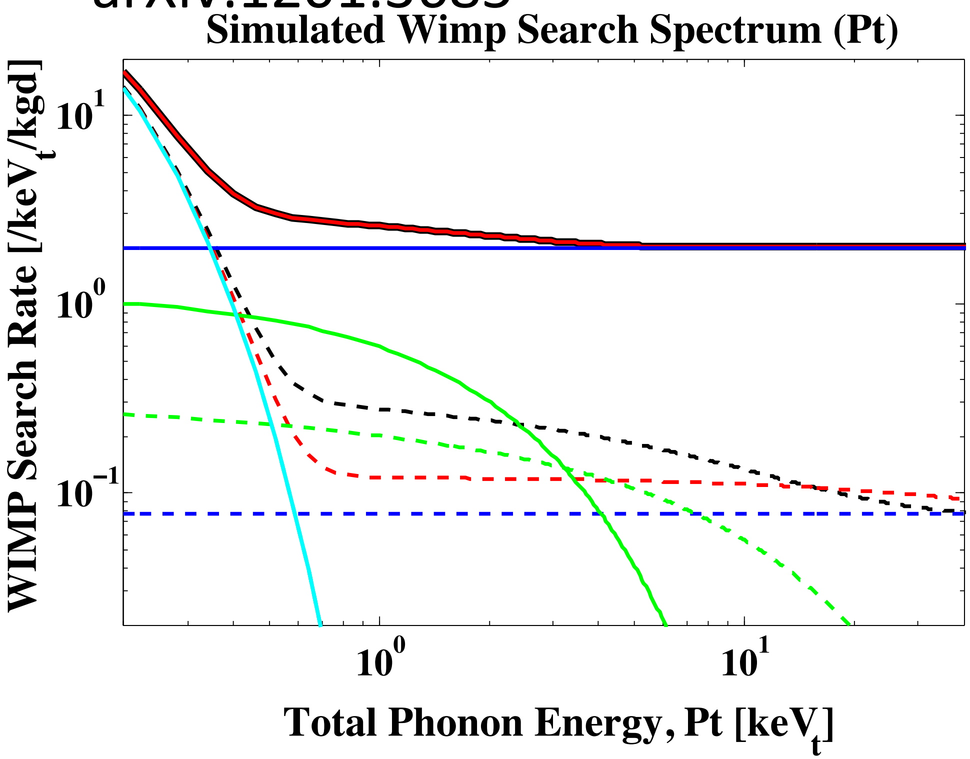
# Summary: Technology R&D

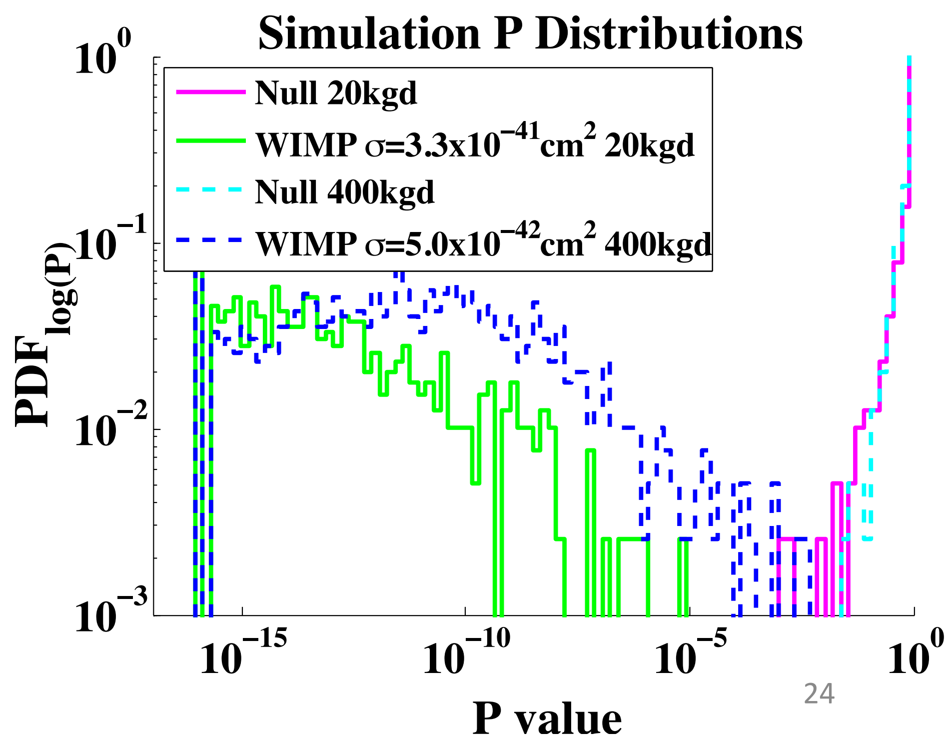
- Noble Gas:
  - Single e$^-$ leakage
  - He (D. McKinsey)
- Low Temperature Semiconductor Detectors:
  - Athermal Phonon Resolution Scaling Law: $\sigma_E \propto T_c^3$
  - Improve Charge Resolution: HEMT preamplifiers
  - Study Luke Gain
    - Systematic Checks for 1MeV-1GeV DM
    - ER/NR Discrimination Luke Gain Discrimination Techniques
- Cross Disciplinary Research:
  - Coherent ν Scattering (low temperature detectors)
    - Sterile ν search
    - Non-standard ν interactions (NSI)
  - ν magnetic moment (S2 only 2 phase Xe TPC)

# Backup Slides

# 1-10GeV ER Background Subtraction

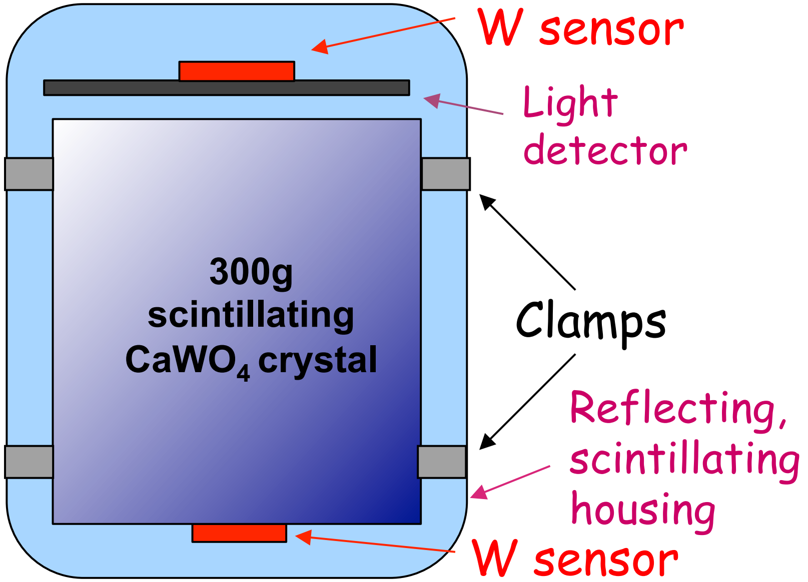
- Vb=0: $E_r$ rate distribution
- Large Vb: Measures $n_{eh}$ rate distribution $E_{tot} = E_r + n_{eh} e V_b$
- Sequential Measurement at both biases
- ER Compton Background Suppressed by x5-x10
  - ER Gain ~ 26
  - NR Gain ~ 2.5 – 5
- arXiv:1201.3685

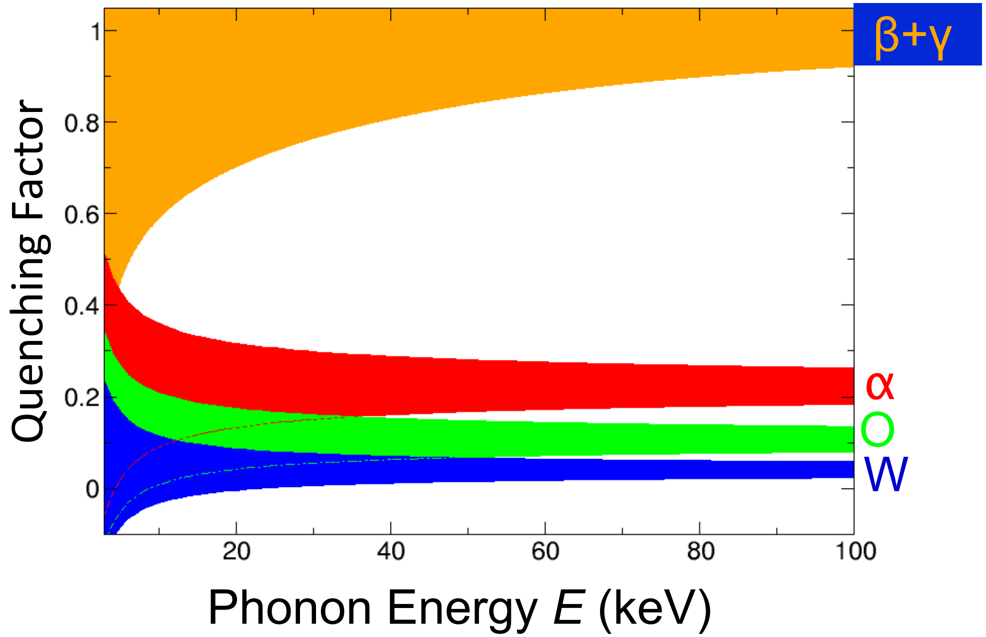


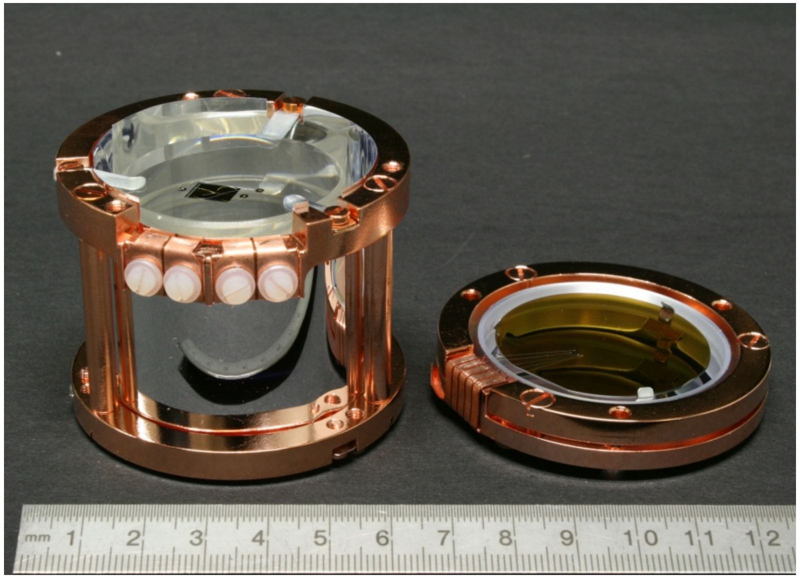



# CRESST

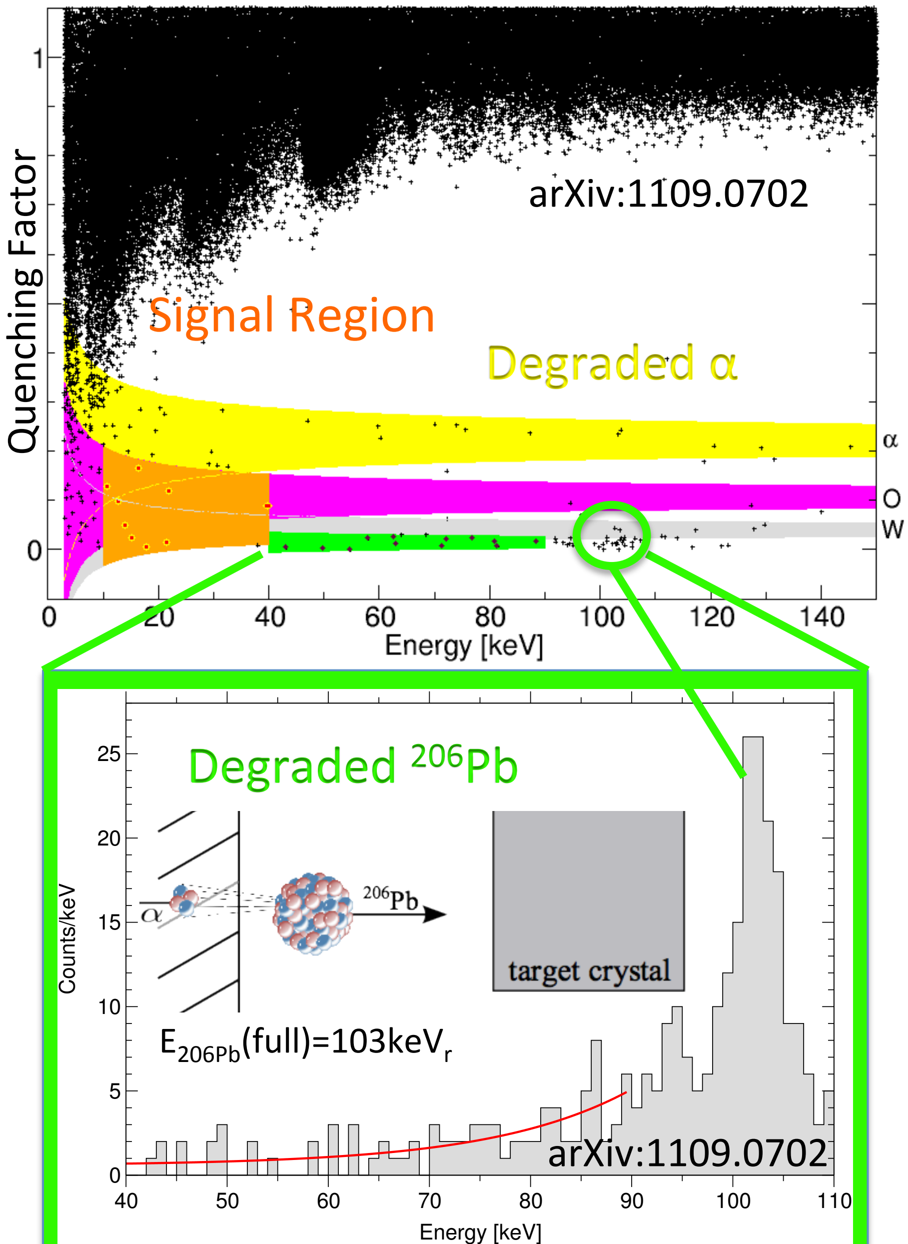
- Phonon and Scintillation
- 8 detectors, 730kgd
- 2% of $E_r$ energy is converted into photons for electron recoils (for CDMS Ge: 25%)
- Analysis Threshold: ~10keV$_r$ >> Trigger/ Energy Threshold
- Multiple Nuclei: Multiple Q
  - $Q_O$~0.1
  - $Q_{Ca}$~0.06
  - $Q_W$~0.04



# CRESST: Results

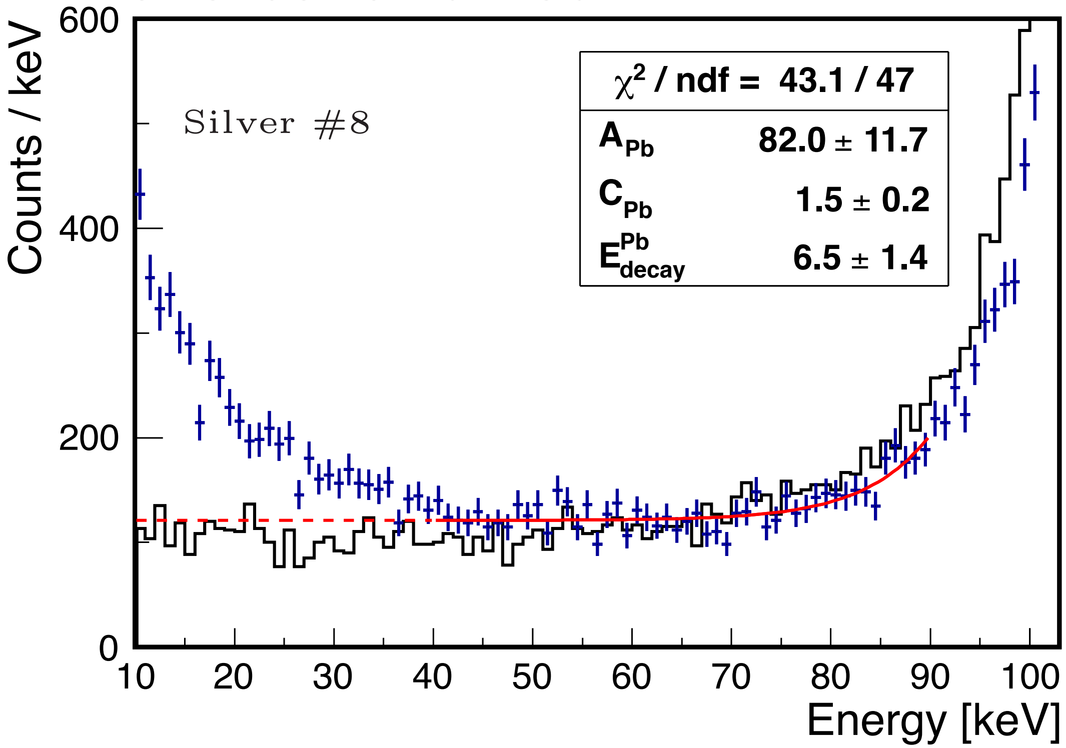


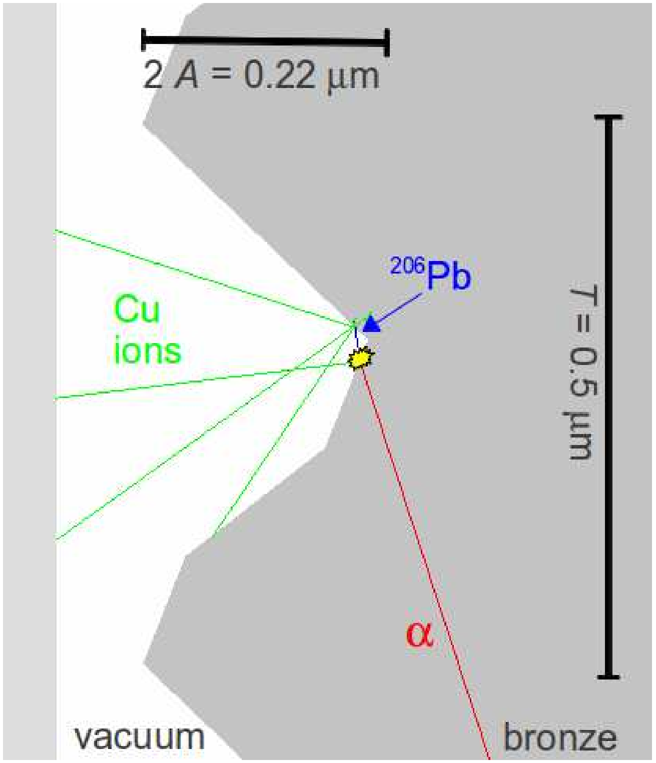

- 67 events within signal region
- Extract background signals by extrapolating from higher energies
- Maximum Likelihood Analysis
- Null WIMP Hypothesis:
  - $P_{M1}$: 4.7σ
  - $P_{M2}$: 4.2σ

| | M1 (W) | M2 (O) |
|---|---|---|
| $e/\gamma$-events | $8.00 \pm 0.05$ | $8.00 \pm 0.05$ |
| $\alpha$-events | $11.5^{+2.6}_{-2.3}$ | $11.2^{+2.5}_{-2.3}$ |
| neutron events | $7.5^{+6.3}_{-5.5}$ | $9.7^{+6.1}_{-5.1}$ |
| Pb recoils | $15.0^{+5.2}_{-5.1}$ | $18.7^{+4.9}_{-4.7}$ |
| signal events | $29.4^{+8.6}_{-7.7}$ | $24.2^{+8.1}_{-7.2}$ |
| $m_\chi$ [GeV] | 25.3 | 11.6 |
| $\sigma_{WN}$ [pb] | $1.6 \cdot 10^{-6}$ | $3.7 \cdot 10^{-5}$ |

# CRESST: Clamp Surface Roughness

- CRESST: Assumed flat surfaces in monte carlo
- M. Kuzniak et al (1203.1576): Spectral shape varies significantly with surface roughness
- Maximal likelihood analysis overconstrained

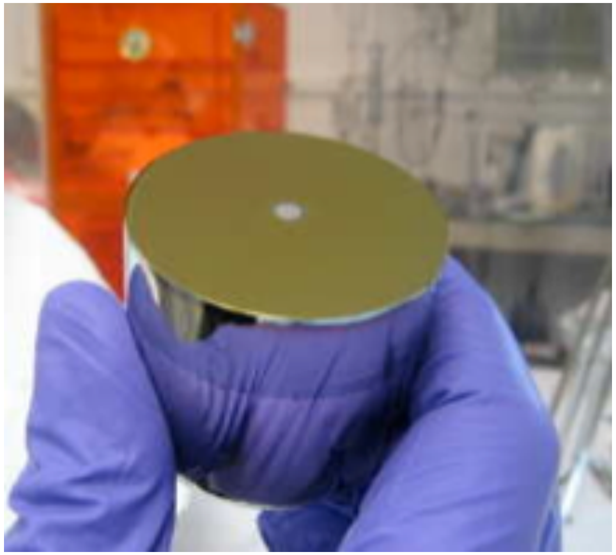


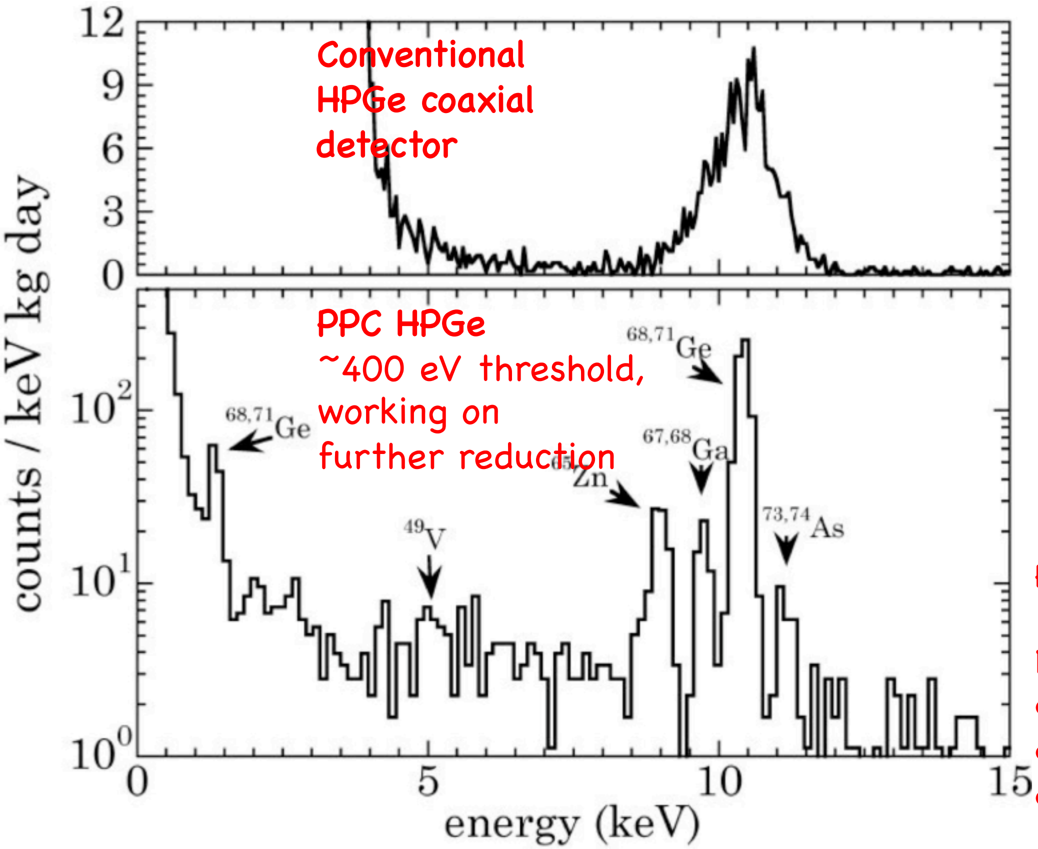




- Future: Decrease Clamp Radioactivity
- No Discovery Potential

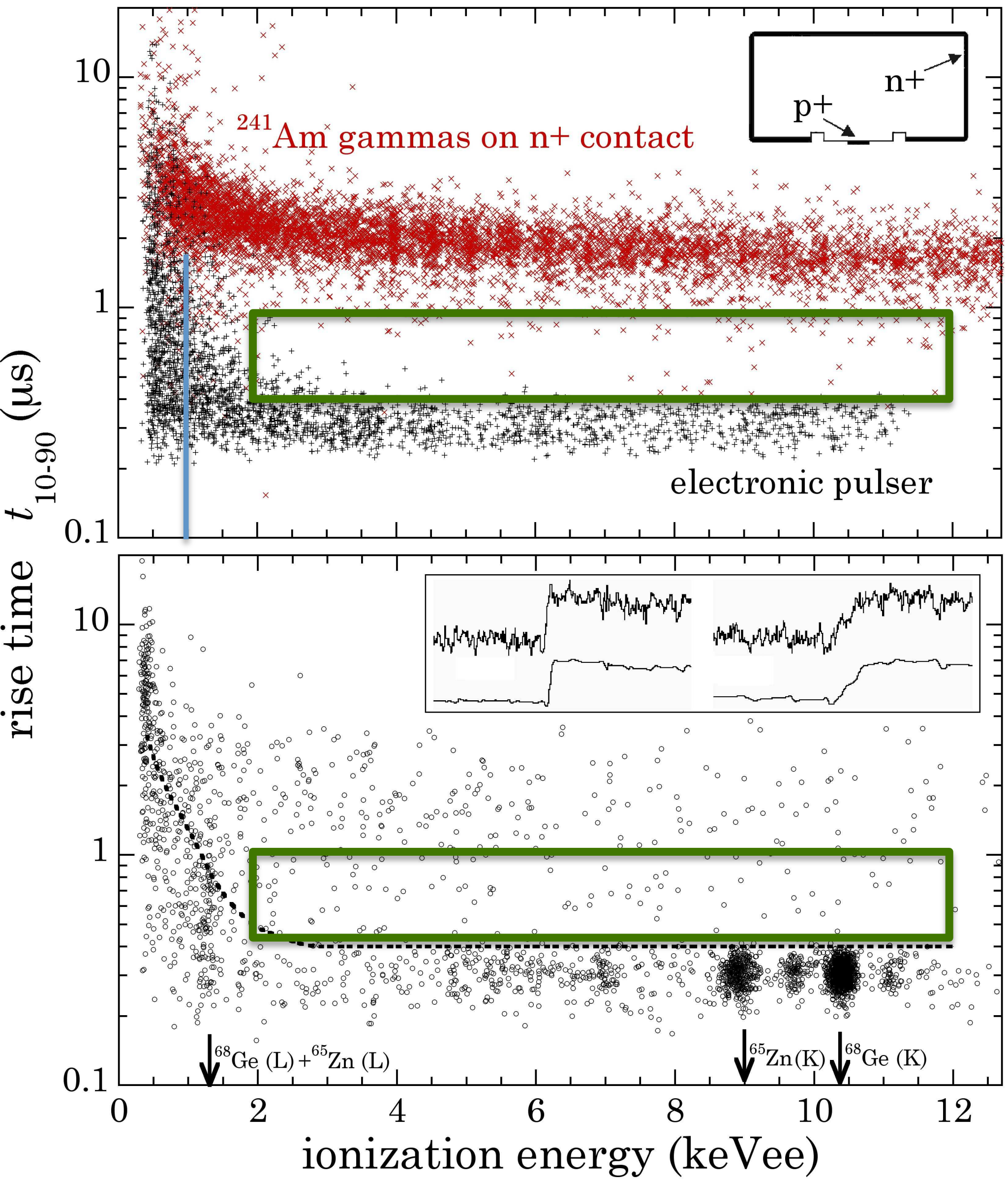
# CoGENT

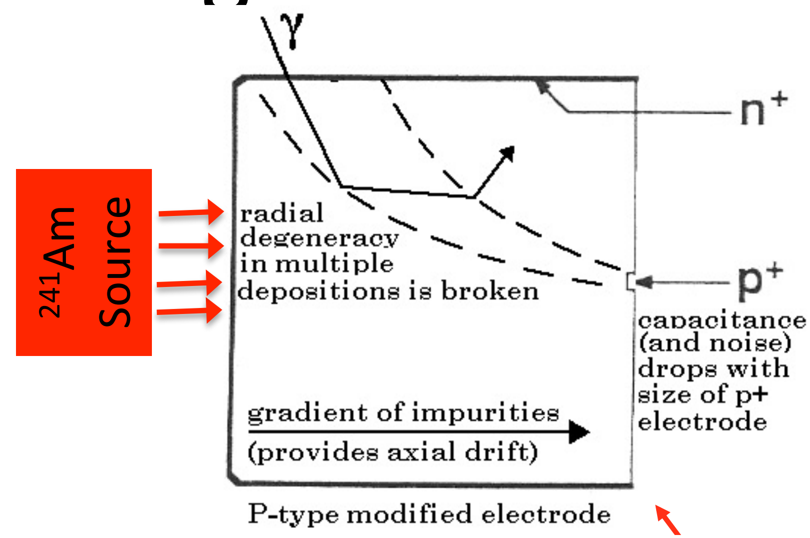
- 440g p-type Ge ionization only detector
- Geometry of $p^+$ electrode shrunk in size for low capacitance and better energy resolution
- $E_{threshold}$ ~$400eV_{ee}$





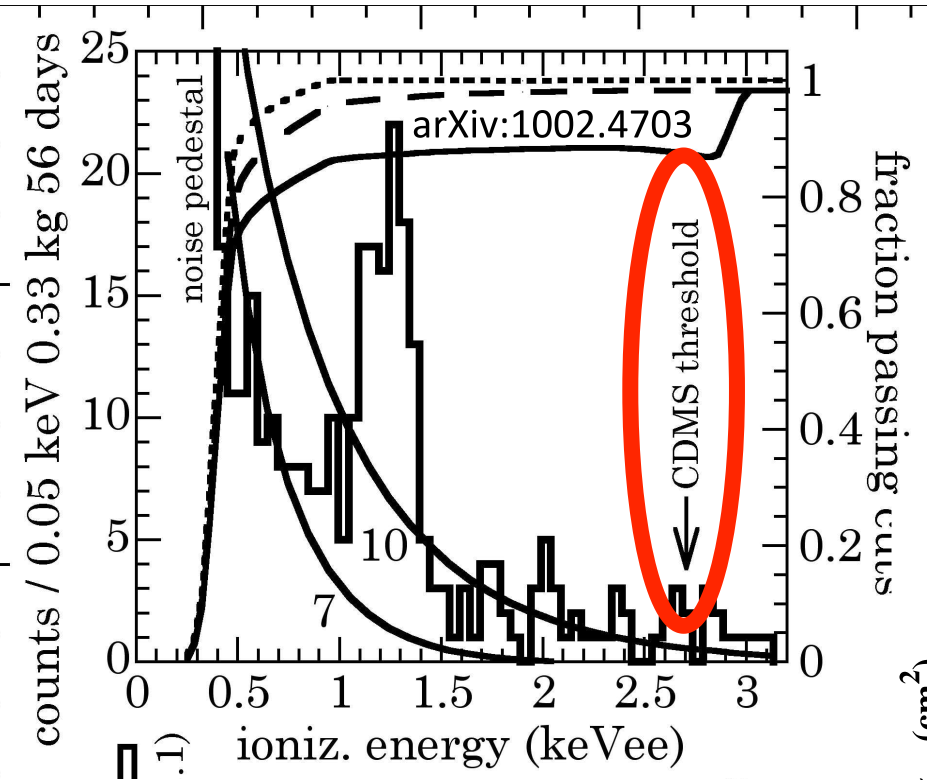
# CoGENT: Position Signal



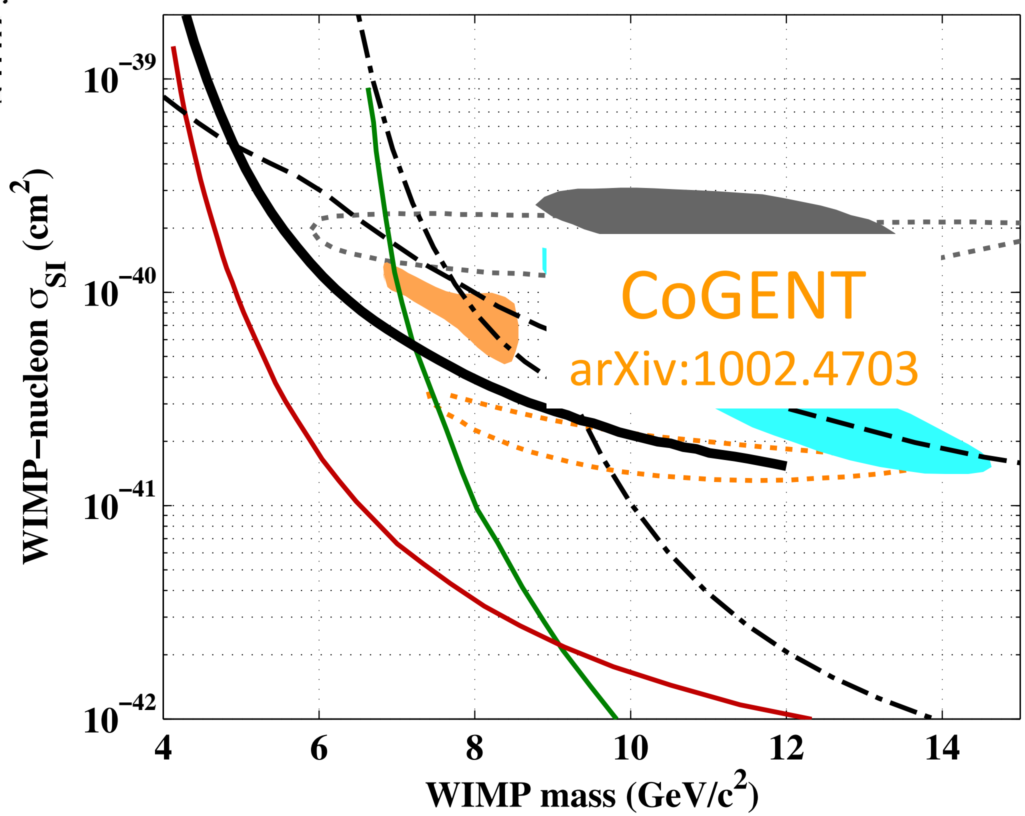

- slow carrier transport near n$^+$ electrode means slow risetimes
- 1002.4703: Surface Event Leakage ~0 for E>1keV$_{ee}$
- Potential Problems:
  - Quasi Collimated Source … position dependence
  - Between band events in background data?

# CoGENT: Unexplained Excess

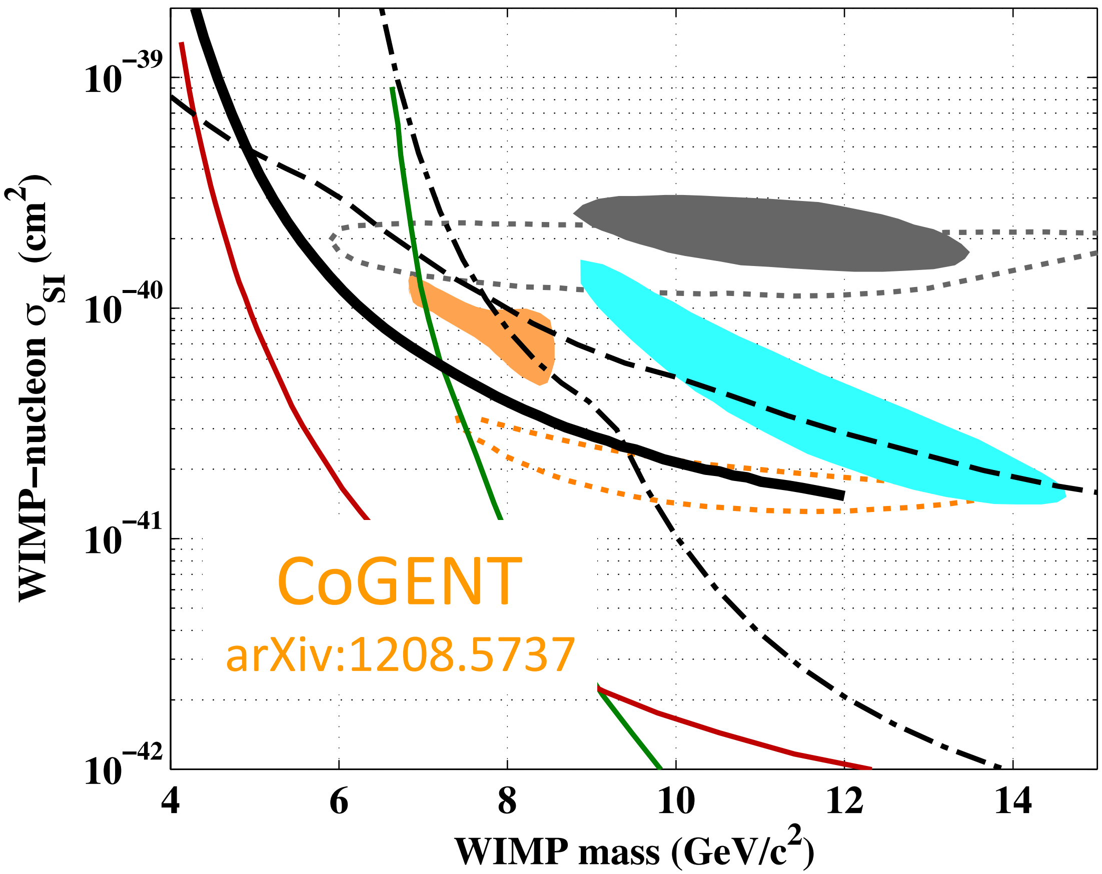



- Unexplained Excess below $3keV_{ee}$
- Even CoGENT's argument starts to break down below $1keV_{ee}$
- Q: Phonons vs Charge ?

- Difference in tone between paper and talks
- CDMS unsuccessfully attempted numerous times to begin a dialogue on timing cut leakage



# CoGENT: Now Background Subtracting!

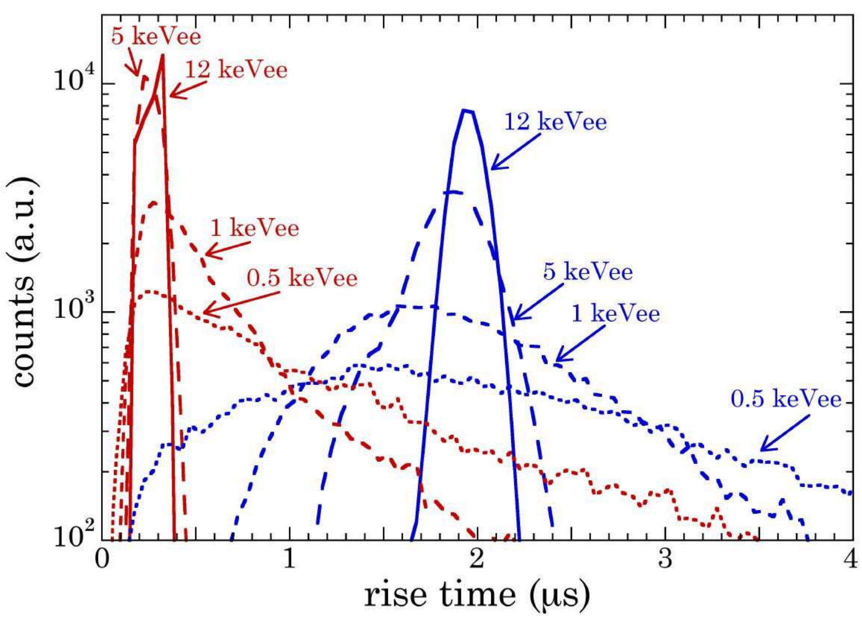



- J. Collar: TAUP Sept 2011
- C. Kelso, D. Hooper et al (arXiv:1110.5338)
- Published on arXiv Just last week (9/2/12) 1208.5737

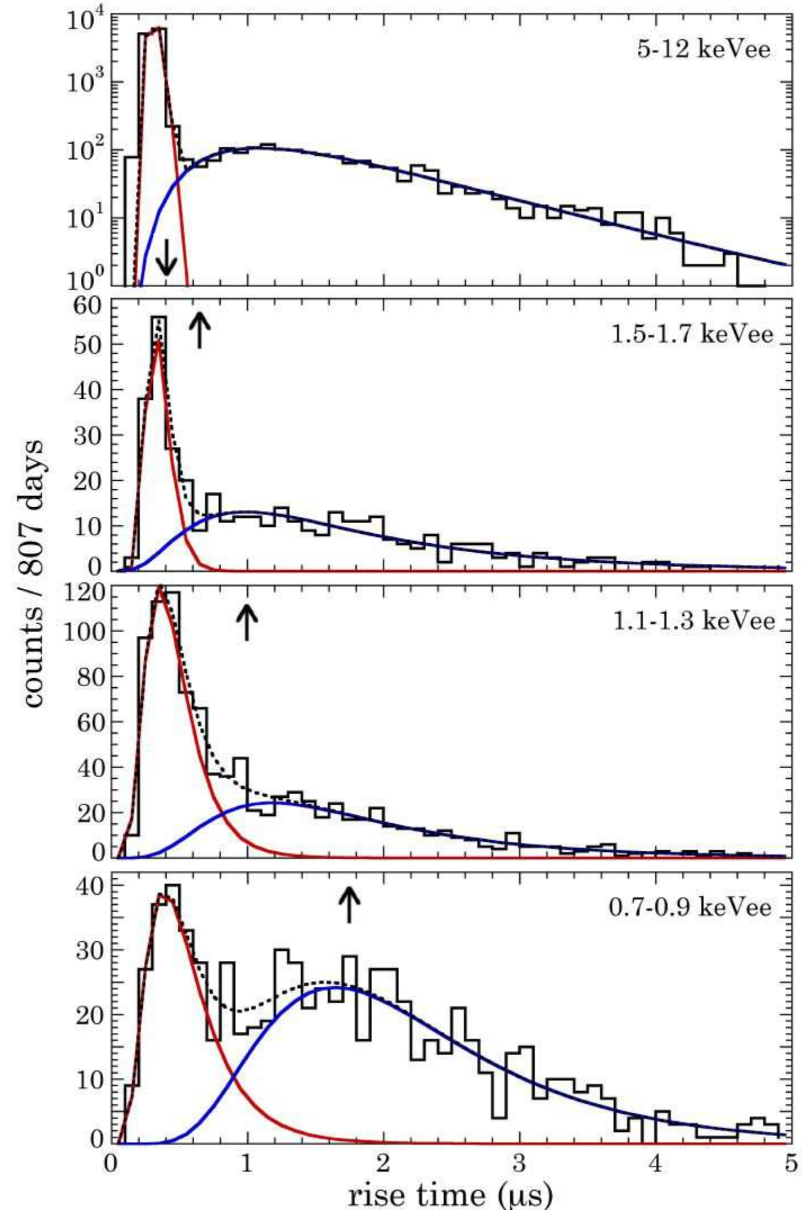
# CoGENT: Background Subtraction

- Impressive Monte Carlo
  - 80% of saved traces are pretrigger
  - Monte Carlo uses actual prepulse noise
- Monte Carlo doesn't qualitatively match data
- Data Fit with log-normal probability distributions
  - Juan: log-normal match monte carlo distributions well
  - Matt: So? Monte Carlo doesn't match data
- Maximal likelihood fits must be tested for functional form systematics (remember )

Monte Carlo




WIMP Search Data



# CoGENT: Modulation

- arXiv:1106.0650(PRL) & arXiv:1208.5737
- Enormous Modulation
  - DAMA: 2% vs CoGENT: >20%
  - 2.8σ statistical signifcance
- More Pronounced in 0.5-3.0keVee bin than 0.5-0.9keVee bin
- Different analyses have different 0.5-0.9keVee modulation signatures
  - WHY?
- Surface Events don't show enormous anticorrelation (nice check)
- Incredibly Stable
  - Noise
  - Threshold
- Modulation is mostly away from trigger
- C. Kelso, D. Hooper, et al: 1110.5338
  - Non-maxwellian structures / Tidal streams required to fit such a huge modulation