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Direct Detection of Dark Matter

Technologies complementary to noble gases

The low and ultra low mass frontier

Four broad classes of models

Situation February 2018

High WIMP Mass

Technologies complementary to noble liquids

The 10 GeV/c^2 region

Signal? How do we check DAMA

The 300 MeV to 10 GeV/c^2 region

Low temperature detectors, CCD's, Gas

1 keV-300 MeV/c^2 Dark Matter scattering

Also 1 meV to 1 keV ultra light boson absorption

Thanks to
Matt Pyle
Kathryn Zurek
and many colleagues
but misunderstandings are mine

15 orders of magnitude in 25'

Theoretical Framework

cf. TienTien Yu's and Kallia Petraki's talk

WIMPs in the strict sense

Particles in thermal equilibrium + decoupling when non-relativistic

Freeze out when annihilation rate ≈ expansion rate

$$\Rightarrow \Omega_{DM} h^2 = \frac{3 \cdot 10^{-27} cm^3 / s}{\langle \sigma_A v \rangle} \qquad \Omega_{DM} \approx 25\% \Rightarrow \sigma_A \approx \frac{\alpha^2}{M_{EW}^2}$$

Cosmology points to W&Z scale

Inversely standard particle model requires new physics at this scale => significant amount of dark matter

Weakly Interacting Massive Particles

Natural mass range 10 GeV-TeV/c^2

WIMP-like particles

A dark sector which could be as complex as matter sector

Self interacting dark matter, dark photon etc.

could be light mass, involve light mediators

maybe even dark matter—anti dark matter asymmetry

If similar to baryon anti-baryon asymmetry

$$\rho_{DM} \approx 5 \times \rho_{baryon} \Rightarrow M_{DM} \approx 5 \text{ GeV/c}^2$$

Natural scale keV- GeV/c^2

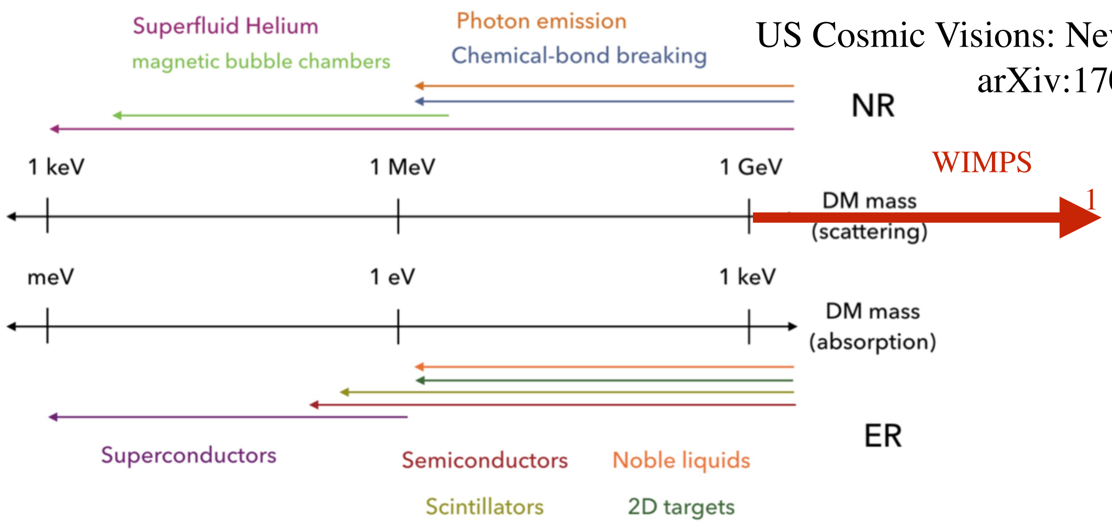
Theoretical Framework

Ultra light bosons

emerging from e.g.,non trivial topologies in compact additional dimensions
Axions, Dark Photons, Moduli etc.
+ QCD motivations
Non thermal production
Because they are very light, large occupation number, best described as coherent field => Coherent methods described for instance in Peter Graham's talk. NOT IN THIS TALK

However, such bosons can be absorbed by either nuclei or electrons.
Same amount of deposited energy as scattering of particle of mass 10^6 more massive: same technology!

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report
arXiv:1707.04591v1



Sterile Neutrinos (not covered in this talk)

Design Drivers for Dark Matter Scattering/Absorption

Maximize potential signal

- Kinematics
- Matrix elements

Maximum sensor energy sensitivity

- Lower gap materials, lower temperature
- or Amplification

Minimize background/dark current/shot noise

- Radioactivity, neutrino background
- External influence (RF, IR, Vibration,Crystal Cracking)
- Gap inhomogeneity (hot spots)

Maximize discrimination

- Energy spectrum shape
- Time and pulse shape
- Nuclear recoil recognition (phonon/ionization or scientillation, pulse shape)
- Directionality? Velocity modulation?

Maximize target mass/unit cost, leverage R&D

WIMP Situation in February 2018

At High Mass >10GeV/c^2

Nothing so far

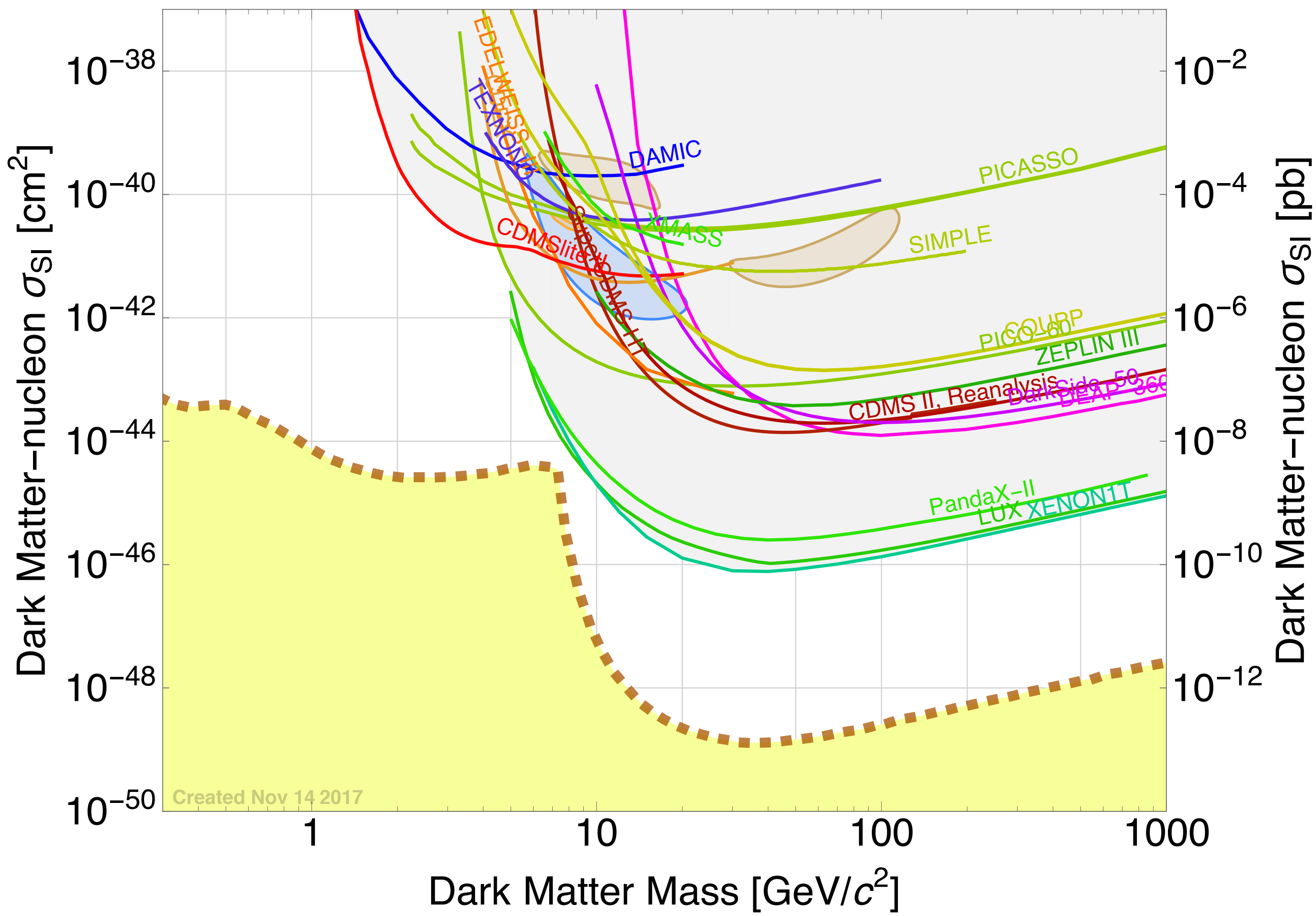
Broadly consistent with the absence of Super Sym. observation at LHC

Focus point solution in CMSSM ≈10^{-45} is mostly excluded

Intermediate Mass ≈10GeV/c^2

A number of closed contours, and strong limits

What is going on?

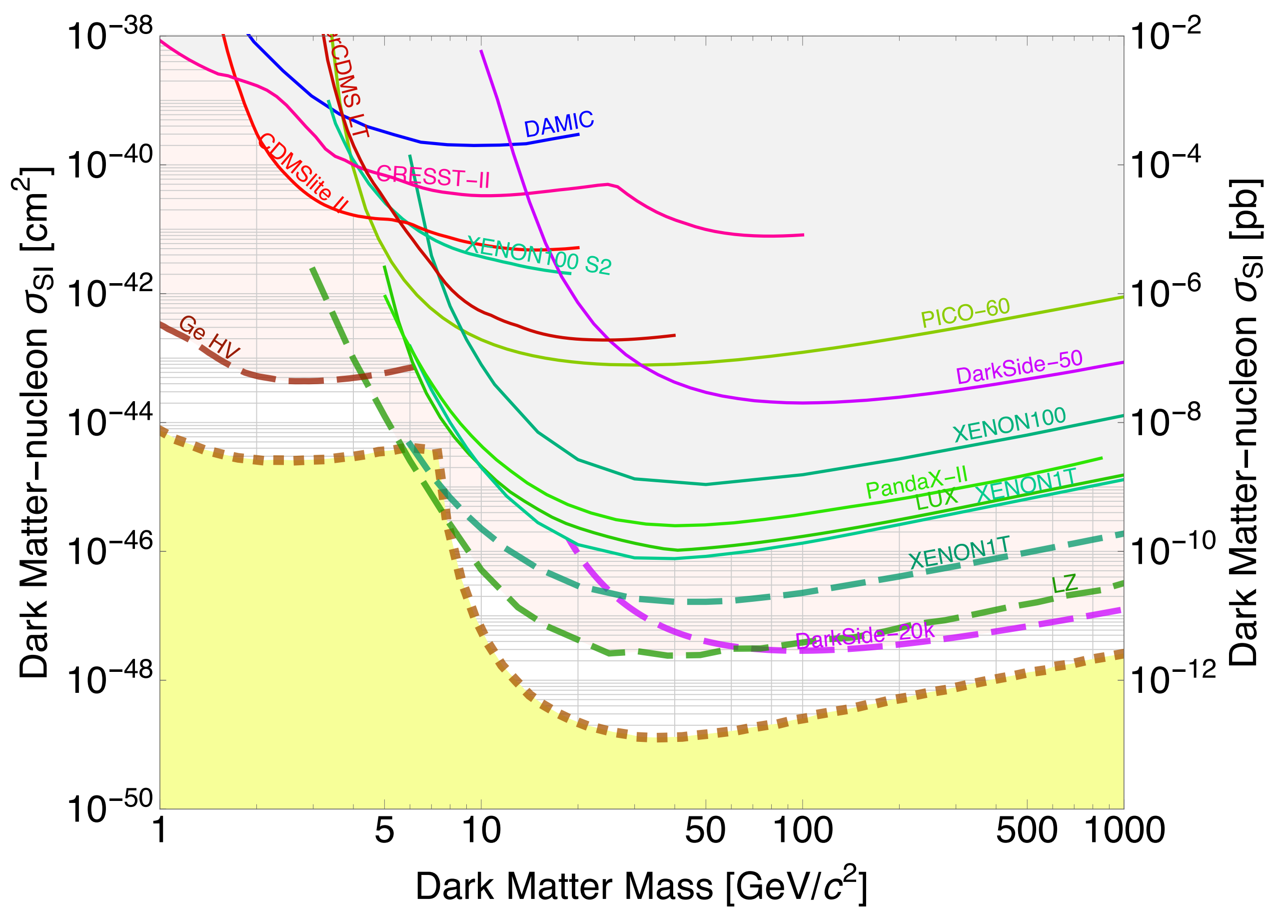


High Mass Region M>10 GeV/c^2

High Mass Region M>10 GeV/c^2

Favored region of WIMP mechanism
Noble liquids are the technologies of choice

- Cristiano Galbiati's review
- Large target masses at reasonable cost
  - Xe excellent self shielding, moderate Nuclear Recoil discrimination
  - (^{39}Ar depleted) Ar excellent Nuclear Recoil discrimination, but higher thresholds



High Mass Region M>10 GeV/c^2

Complementarity of other technologies

Diversity of nuclei: More general than spin independent/dependent

Velocity dependent effects (including Fermi)Haxton, Zurek

Different systematics (but of course need to be in the same sensitivity region)

Large target mass candidates

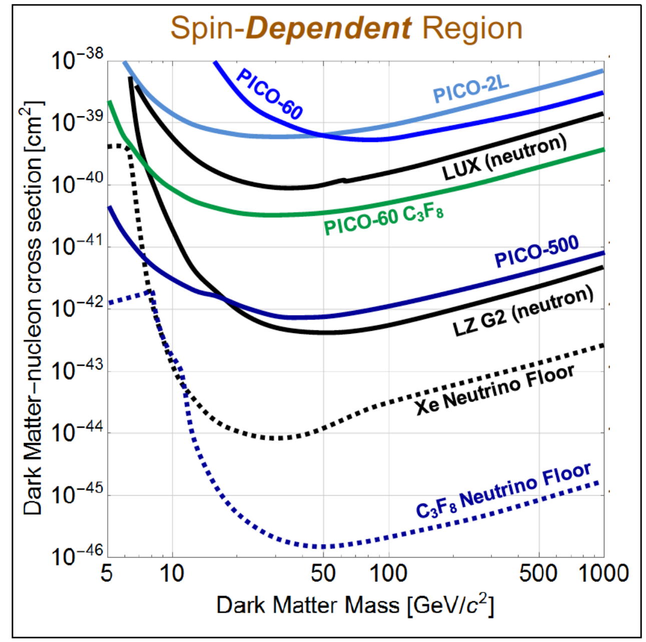
Scintillators (NaI):

challenge of radioactivity but need to check DAMA

PICO

Mostly for “spin dependent”

Discrimination against alphas



Other technologies more suited to lower mass

Ge point detectors:CDEX, CoGeNT II, Majorana (Othman’s talk)

Low temperature detectors: SuperCDMS, EDELWEISS,CRESST

Gaseous detectors: e.g., NEMS-G Spherical

Directional detectors: DRIFT,DMTPC,NEWAGE

=> CYGNUS

Interesting R&D but

Relatively high threshold and low target mass

(Snowden-Ifft’s talk: using DRIFT at accelerators)

The 10 GeV/c^2 Region

A 10 Gev/c² WIMP ???

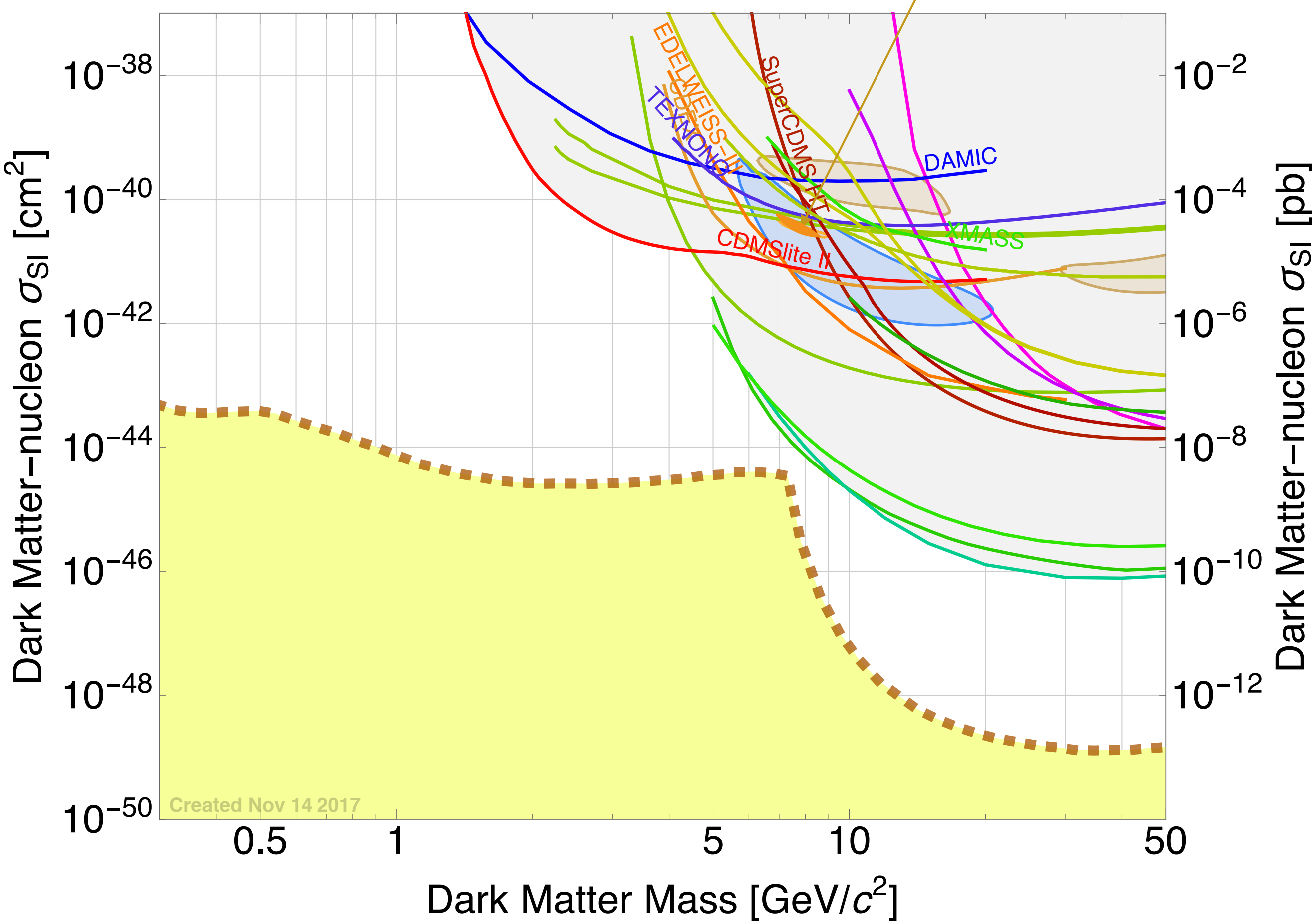
2014: wave of optimism

- Accumulation of claims in that region
- DAMA
- CoGeNT
- CRESST
- CDMS Si (no claim)
- Just the region expected for asymmetric dark

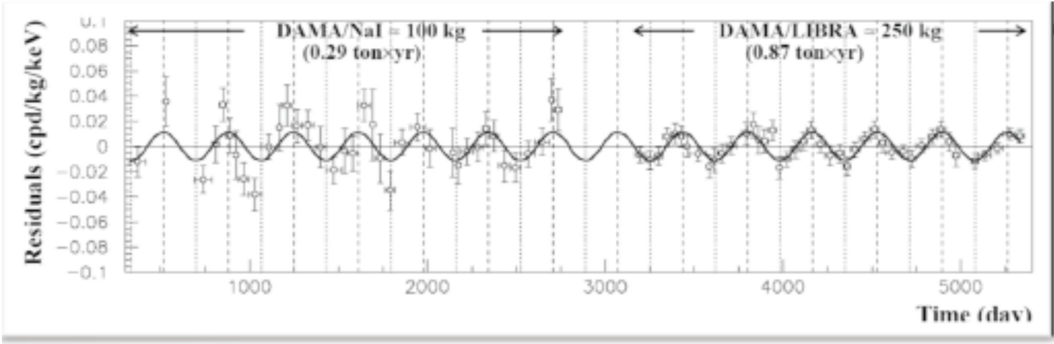
2018: Unlikely

- Exclusion by well calibrated experiments
  - XENON 100,Xenon1T
  - LUX
  - Panda X II
  - SuperCDMS Soudan
  - CDEX
- The latter two experiments are Ge cannot be explained by nuclear physics
- Outliers close to threshold!

CoGeNT probably incorrect cannot be nuclear physics



NaI: How to prove/disprove DAMA



Clearly modulation
although not blind

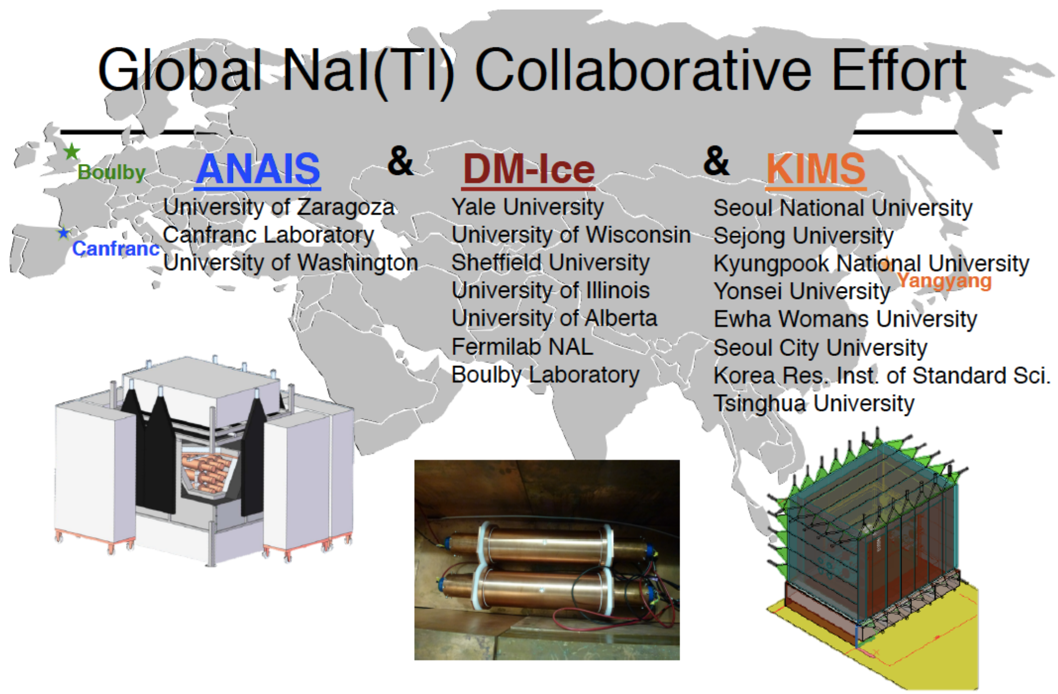
Is it Dark Matter or instrumental?

How do we make progress (NaI)?

Lower threshold: LIBRA has changed Phototubes to high QE Results 2017
(Caracciolo's talk)

Experiments by other groups: DM-Ice,ANAIS,KIMS, SABRE

ANAIS 112 (Marisa Sarsa's talk)
COSINE-100 (Reina Maruyama's talk)
SABRE (Burkhant Serfu)



How do we make progress (Other technologies)?

Natural for
CDEX, CoGeNT II, Majorana

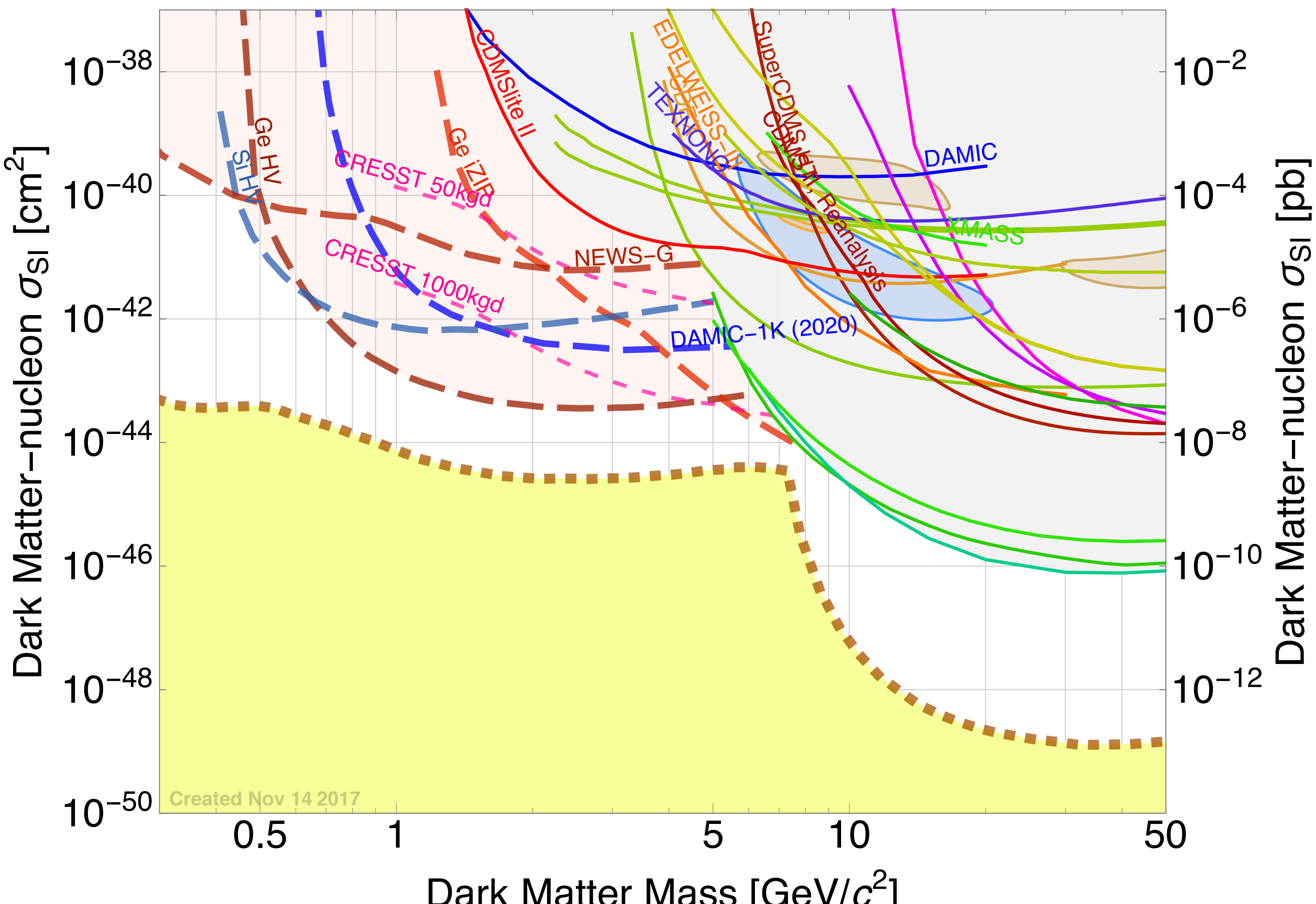
Noble Liquids (new Darkside result!)

The Low Mass Region
300MeV/c^2<M<10 GeV/c^2

Low Mass Region Projections

≈2020

DAMIC/SENSEI CCD
NEWS-G (Spherical Proportional Counter)
Low temperature calorimeters: SuperCDMS, CRESST, Edelweiss)



SuperCDMS SNOLAB example

G2 Project funded by DOE, NSF, Canada

Recent successful C2/CD3 review

=> official authorization to build in mid March
Based on:
Maturity of designs
Detectors
- Can hold the electric field needed in our HV detectors to
- Evidence at zero field that we can significantly exceed the threshold resolution of the project (<50eV r.m.s.)
- Cannot measure resolution at high voltage at surface facilities
  - We plan to do it at CUTE (SNOLAB) coming online this summer 2018

cf Ben Loer's talk on Friday

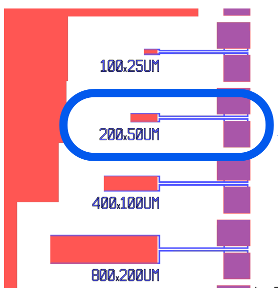
For this talk

What have we learnt in particular for going to lower mass
cf Rob Calkins' talk
What we need to do to go down to the neutrino floor

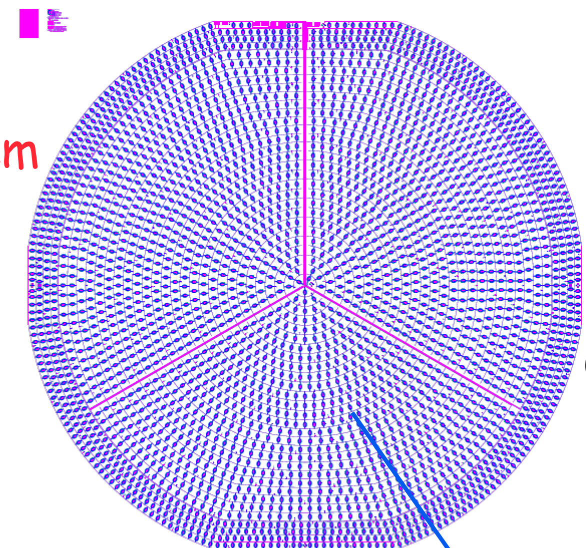
Current Limits on resolution

In principle TES r.m.s. ≈T_c^3 (Pyle)
But need to control

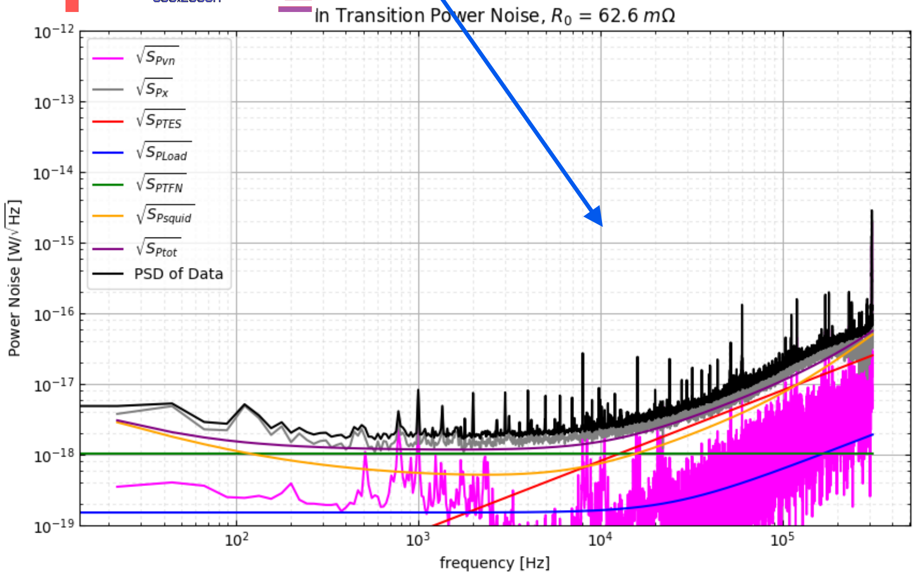
- Vibrations √
- IR √
- RF <= seems to be a major problem

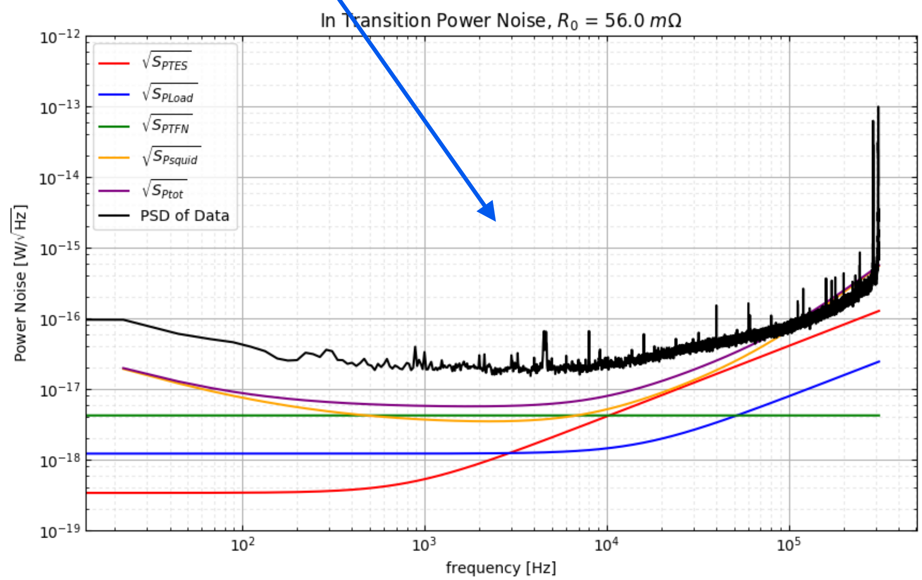


Compact TES
50μx200μ
2 10^{-18} W/√Hz



Distributed TES
Collect over 4″
2 10^{-17} W/√Hz





Low E-field Dark Current

Luke Neganov amplification

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

Need to hold voltage

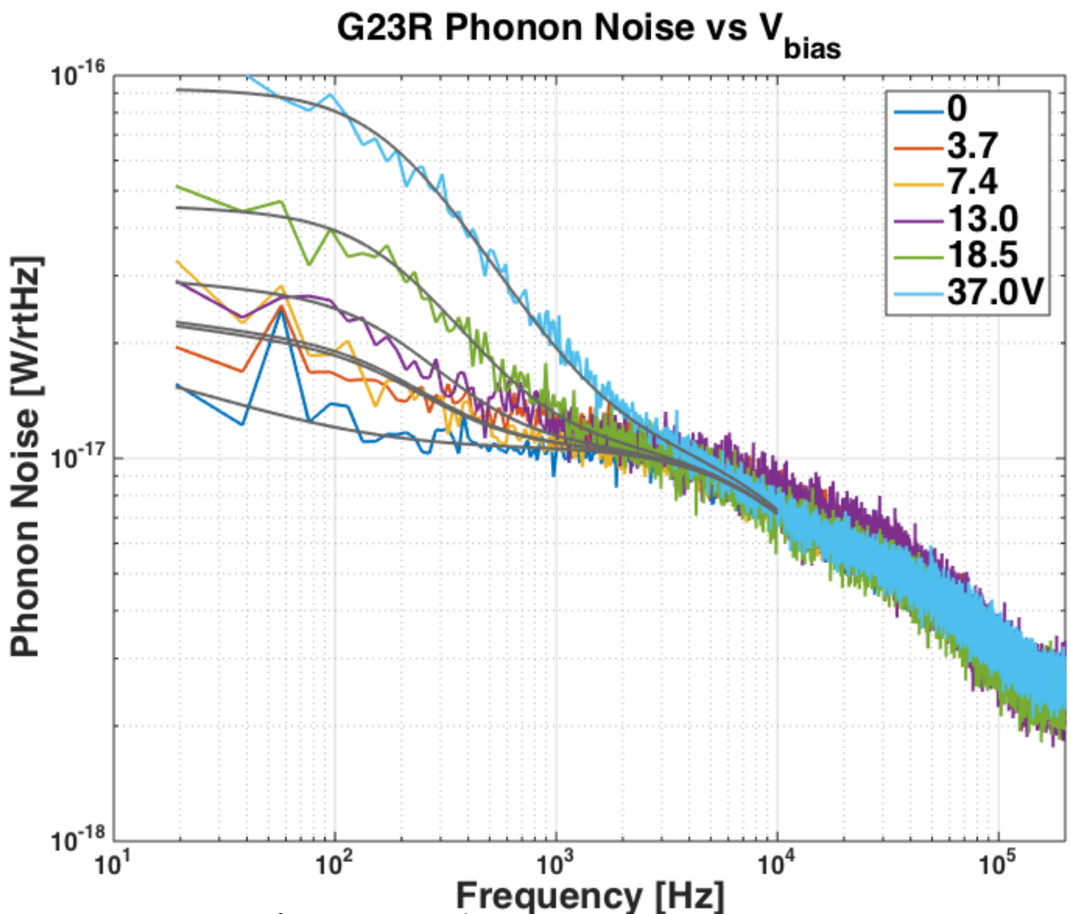
Delicate but our contact seem OK

However large dark current

≈ independent of field

IR ? Metastable state

Appears as shot noise



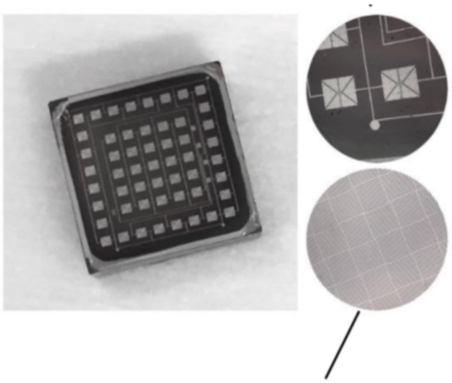
an early R&D detector

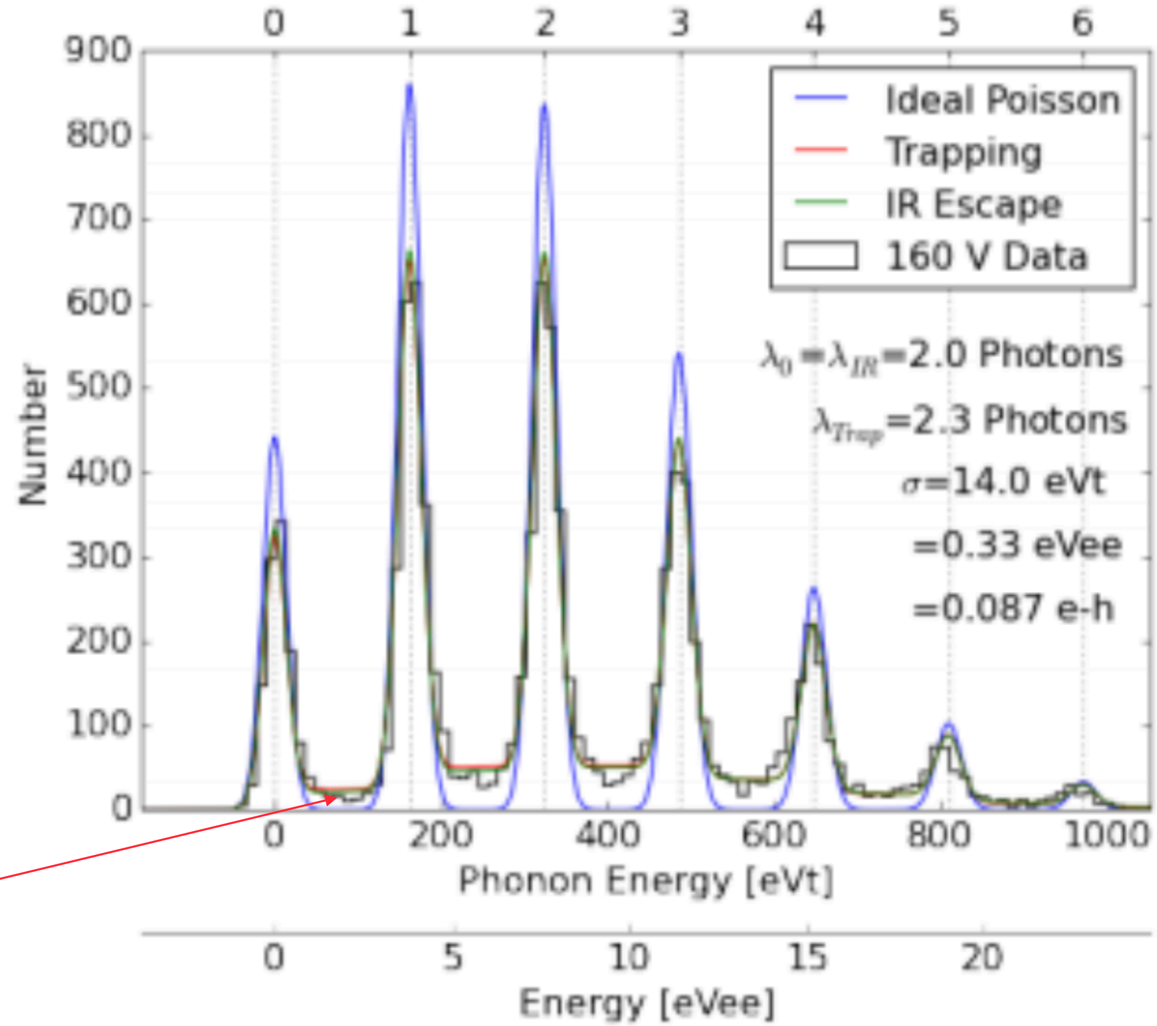
significant improvements since

Maybe due to being at the surface

Plan to test at CUTE

First observation of single $e^{-}h^{+}$ pair





G2+ Goal. Detect e-h+

requires <10eV

We do not have it yet

=Go to small detector

1g, 14. eV r.m.s.

Romani et al.arXiv:1710.09335

Excellent diagnosis tool

IR (we now do much better)

Metastable auto-ionizing states

Trapping

Impact ionization

Dark Matter limit

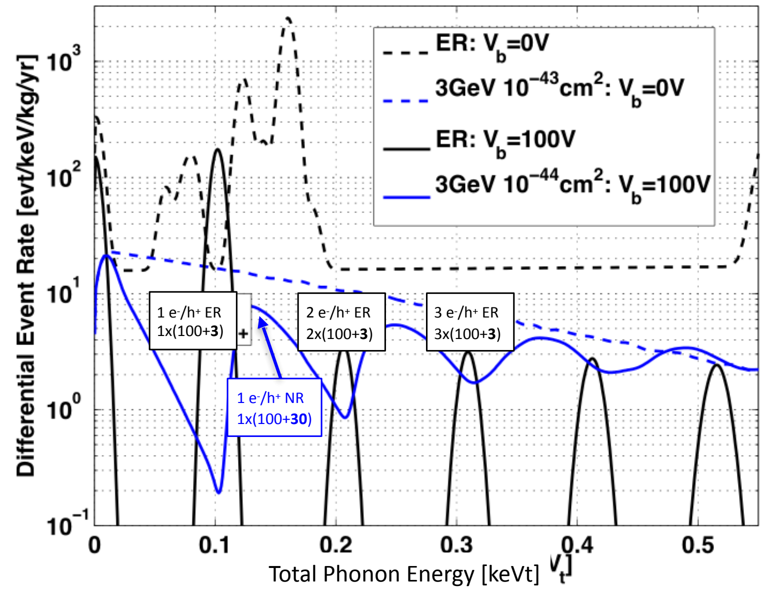
Restoring Nuclear Recoil Discrimination

Luke Neganov amplification mix primary phonons with ionization generated phonons.

How can we restore?

1) Displacement of NR peaks

- $\sigma = 5eV_t$
- Single e-/h+ Sensitivity
- ER/NR Discrimination



2) 2 types phonon sensors

One close to region where Luke Neganov are created
One further away more sensitive to original phonons
=> Separate E0 from ELN

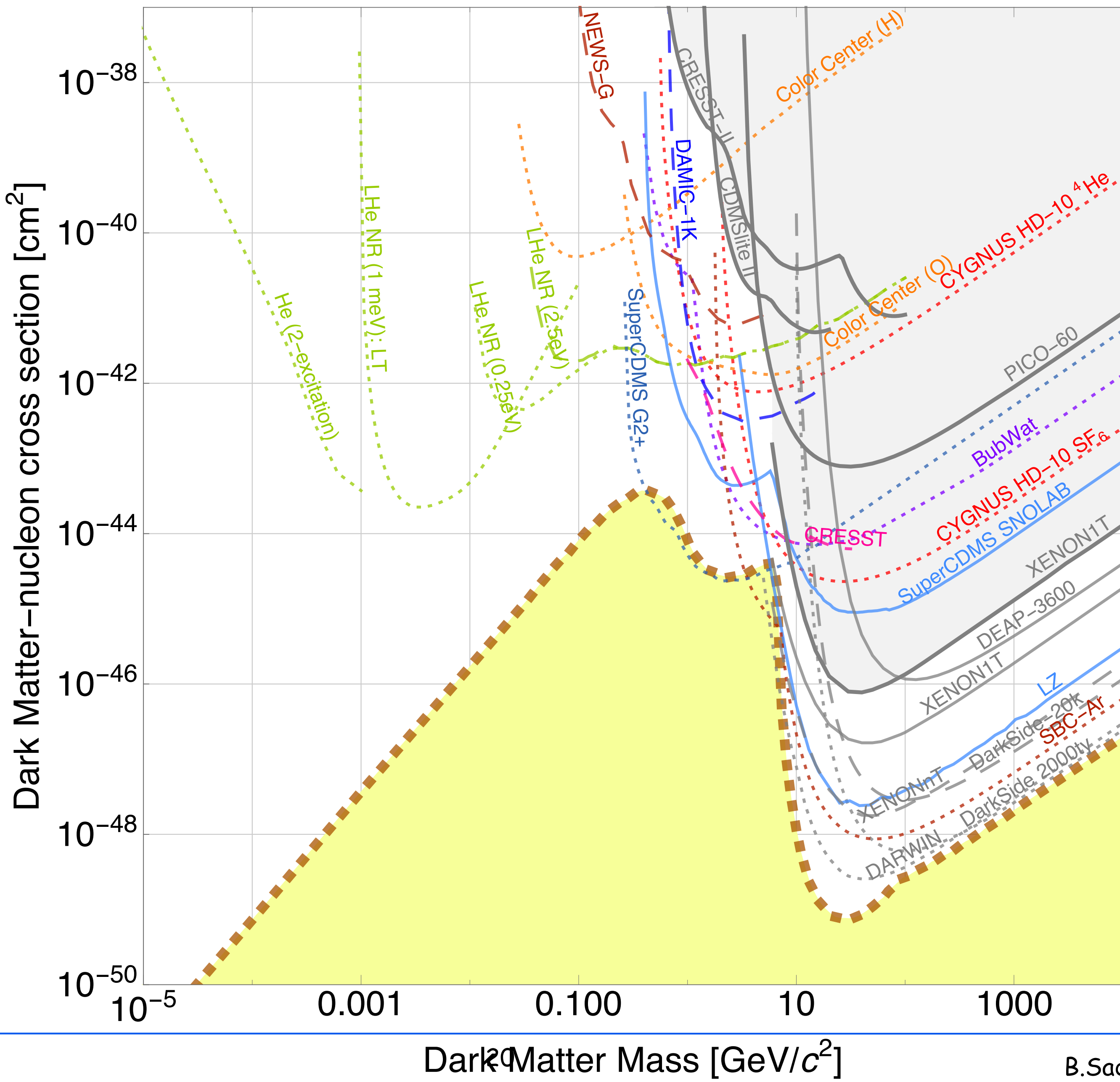
3) Also progress in ionization charge amplifier

(91 eV rms for 300pf detector capacitance)

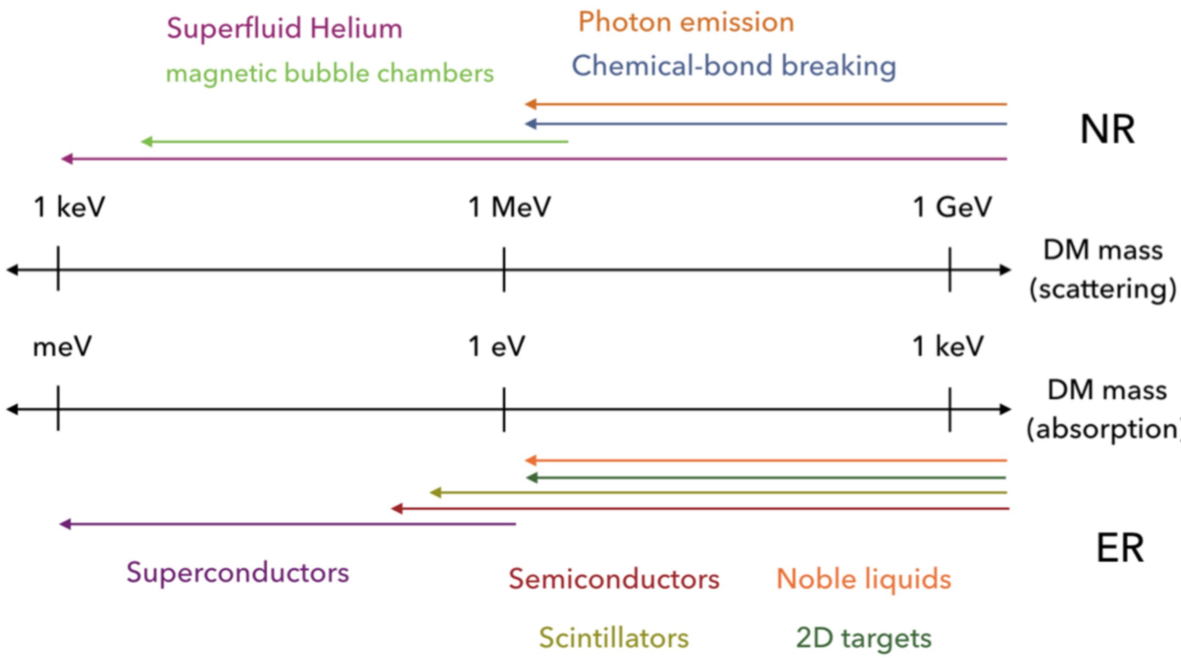
The Ultra Low Mass Region

Our Low Mass Dreams

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report
arXiv:1707.04591v1



The Ultra Low Mass Frontier



How do the creative schemes proposed align to the major design drivers?

1. Maximize potential signal
2. Maximum sensor energy sensitivity
3. Minimize background/dark current/shot noise
4. Maximize discrimination
5. Maximize target mass/unit cost, leverage R&D

1. Maximize Potential Signal

Kinematics

Purely elastic

$$E_d = \frac{|\vec{q}|^2}{2m_T} = \frac{m_r^2}{m_T} v^2 \left(1 - \cos\theta^*\right) = \frac{m_\chi^2 m_T}{\left(m_x + m_T\right)^2} v^2 \left(1 - \cos\theta^*\right)$$

where m_T is the mass of the nucleon or electron

$$\text{For } m_\chi << m_T, \quad E_d \approx \frac{m_\chi^2}{m_T} v^2 \left(1 - \cos\theta^*\right)$$

ultimately due to the conservation of energy and momentum.

Bad news for low mass

But in condensed media, nothing is really free:

excitations, e.g. electrons/holes, quasiparticles, phonons

Interesting calculations e.g., by the Zurek group of multiple excitations

e.g., back to back phonons (≠ large momentum compared to energy carried by phonons)

Penalty due to off shell process, but some sensitivity!

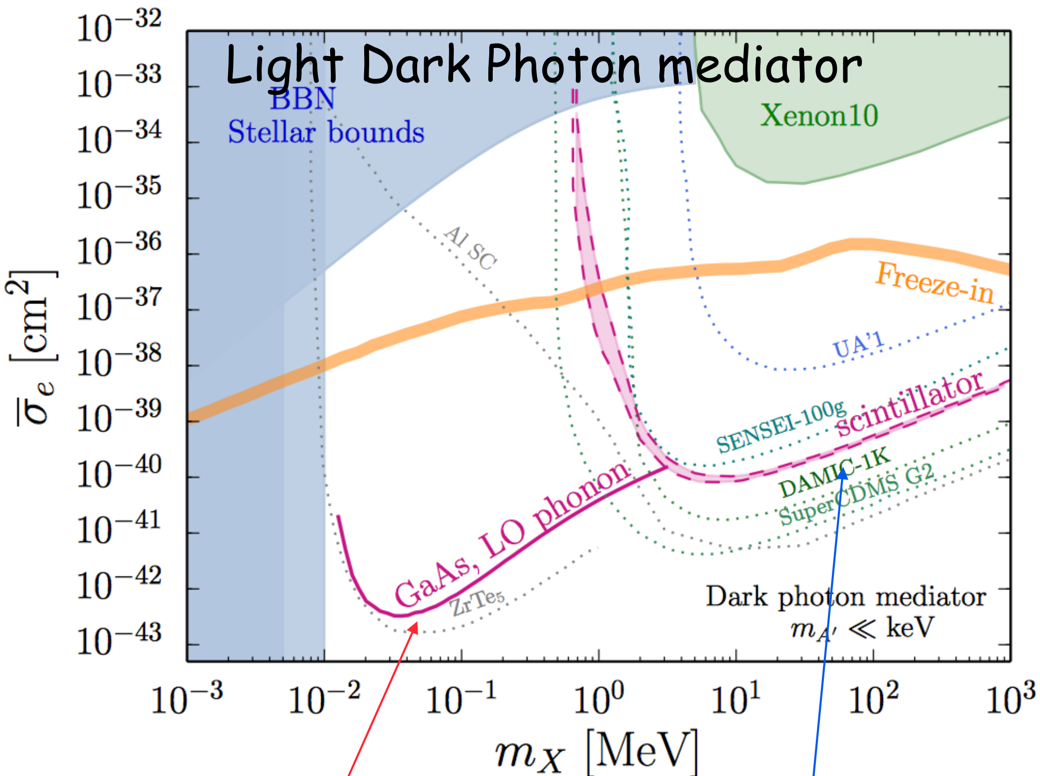
Couplings

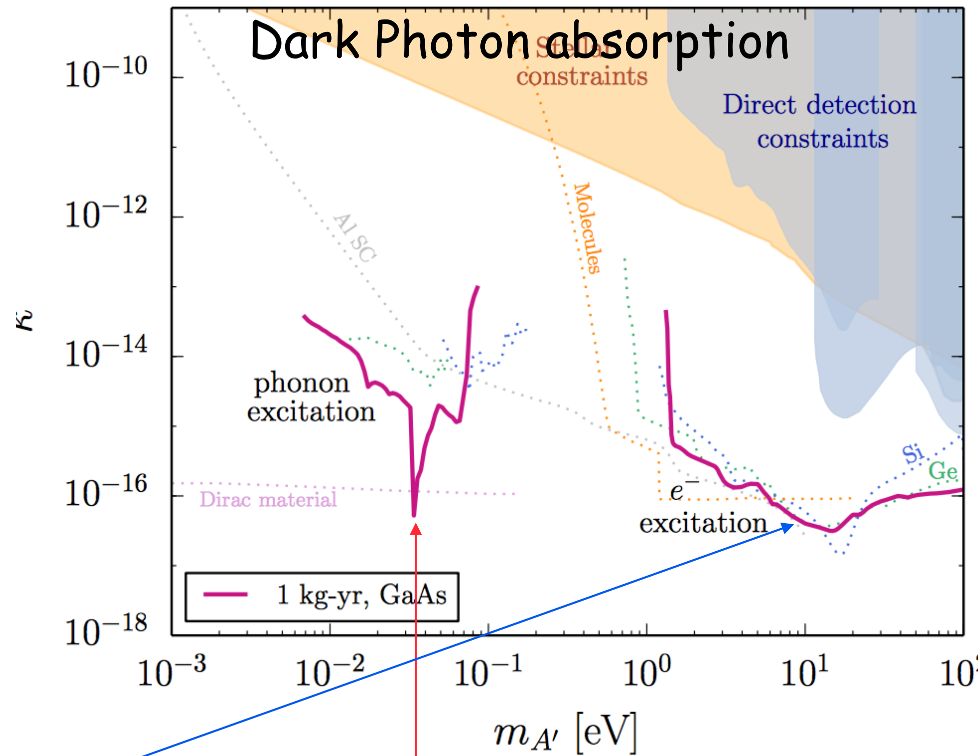
In many dark sector models, coupling to nuclei/electrons is through dark photon and its small mixing with ordinary photons

Advantage of polar crystals, e.g., GaAs, Al_2O_3

arXiv:1712.06598v1 (Knapen, Lin, Pyle, Zurek) including coupling to L Optical phonons

Polar Crystal Example: Dark Photon couplings





LO phonon Production needs 36 meV sensitivity

Scintillation
Direct gap:
Photon threshold = e threshold

LO phonon resonant absorption needs 36 meV sensitivity

2. Maximum Sensor Sensitivity

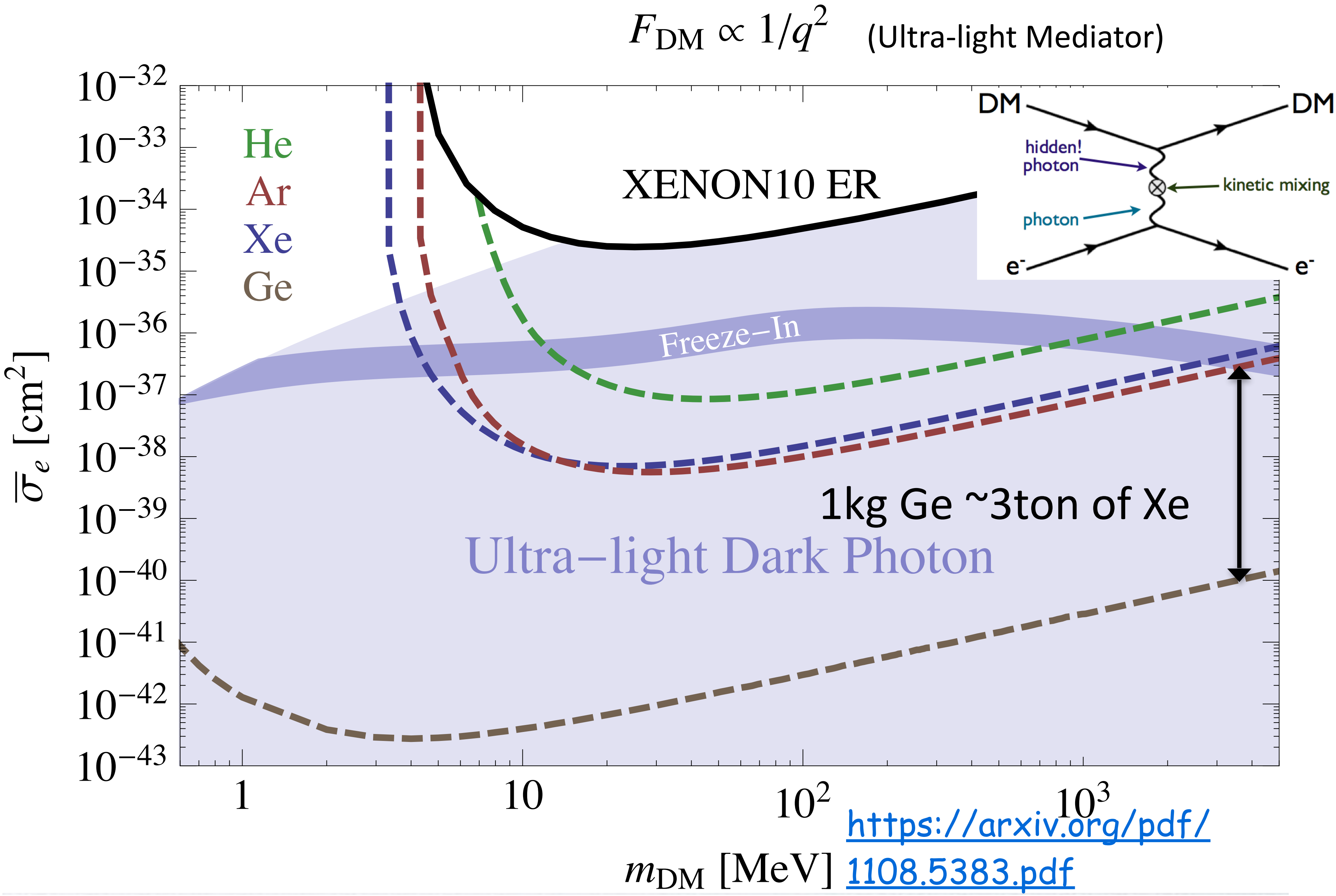
Looking for small gaps

Semiconductors ≈ 1eV (scintillation in Ga As is also 1 eV)
Liquid helium rotons 0.75 meV
Superconductors 1 meV

Creative exuberance which is refreshing (cf 1985)

- Graphene and carbon nanotubes where gap can be engineered
- Dirac materials (Semi metal with small gaps)
- Spins in a magnetic field
- Labelled DNA (Druikier) ≈eV binding energy
- Color centers ≈ eV binding energy?

Smaller Band Gaps are Better



https://arxiv.org/pdf/1108.5383.pdf

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- Dirac materials (Semi metal with small gaps)
- Spins in a magnetic field
- Labelled DNA (Druikier) ≈eV binding energy
- Color centers ≈ eV binding energy?

Need to couple to a sensitive enough sensor

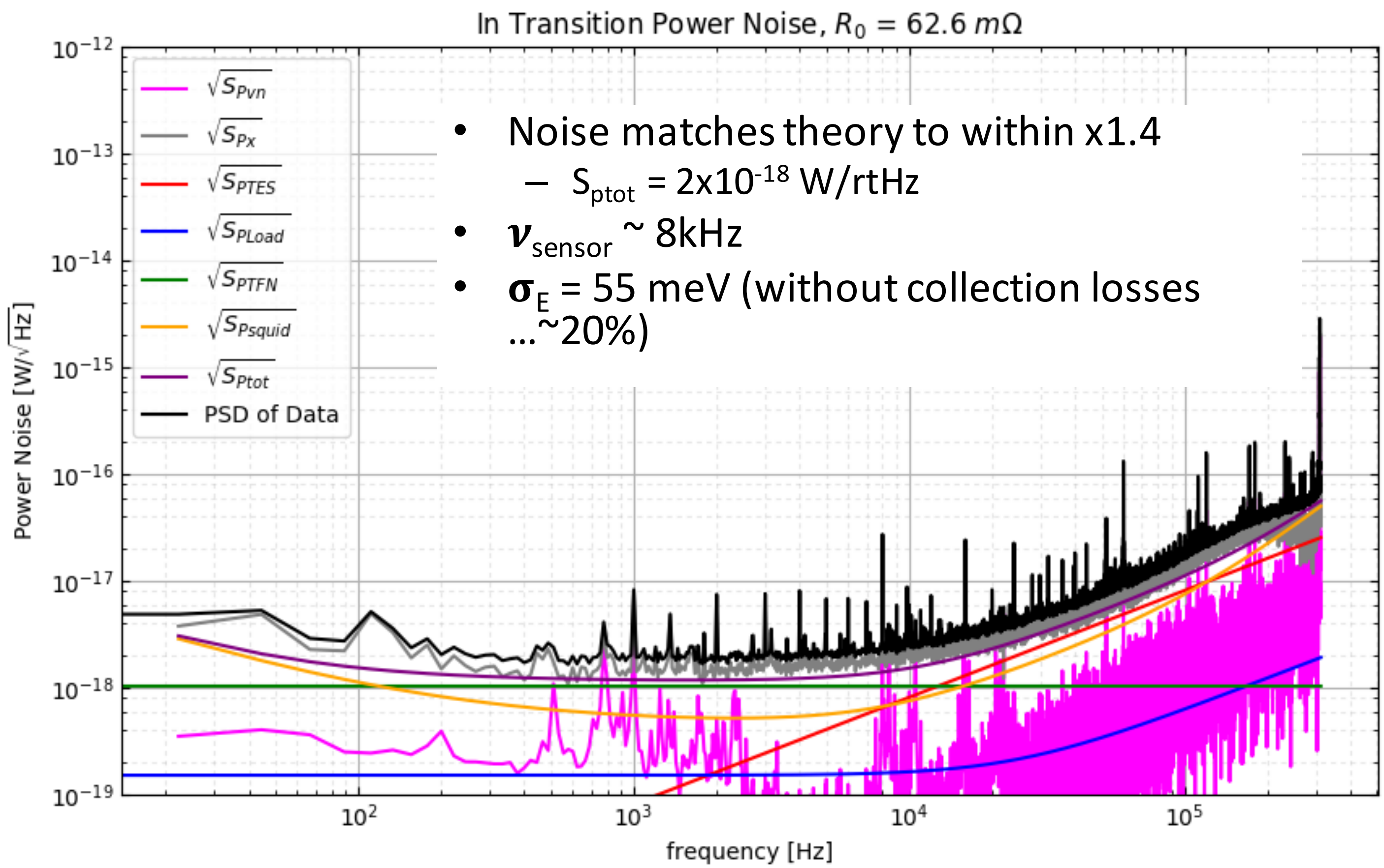
CCDs with skipper readout (multiple sensing) SENSEI but 1 eV

Low temperature sensors

- TES $\approx T_c^3$
- MKID (see talk by Miguel Daal)

Promising TES result: 55 meV

50μx200μ



- Noise matches theory to within x1.4
  - S_{ptot} = 2x10^{-18} W/rtHz
- ν_{sensor} ~ 8kHz
- σ_E = 55 meV (without collection losses …~20%)

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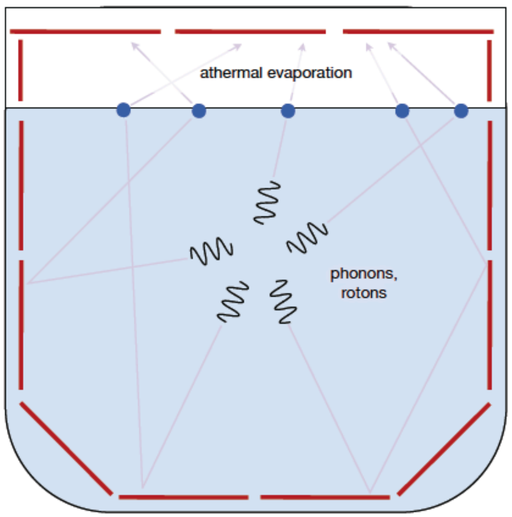
Amplification mechanisms

Luke Neganov but amplifies only ionization
^{4}He Absorption on bare surface

Amplification

Superfluid He: Many Long Lived Excitations



Collected by Excitation Detector above the surface

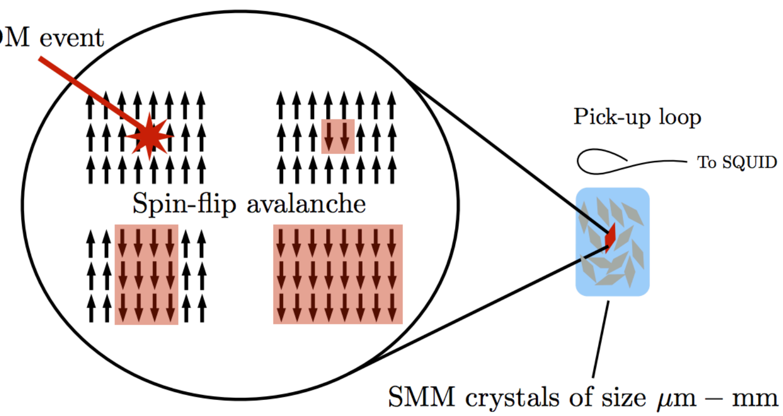
Multiplication by adsorption 9eV on

Spin avalanche

A revival of

the superconducting granules idea!

similarity with metastable liquids (PICO)



3. Minimize Dark Count

4. Maximize Discrimination

My main worry

Fabrication defect=>zero gap flooding the sensors

All parasitic phenomena will

Can we recognize nuclear recoil?

probably not below a few 100MeV

Directionality

inherent in crystal asymmetries

e.g., Al_2O_3 LO phonons (Zurek, Pyle)

5. Target Mass and Cost

Rate goes at $1/m_{DM}$!

$$R = \sigma n_{DM} N_{exp}$$
$$= \sigma \frac{\rho_{DM}}{M_{DM}} N_{exp}$$

We will probably see soon results with very small detectors

- DAMIC/SENSEI
- Low Temperature Detectors R&D (e.g., SuperCDMS)

Do not underestimate cost of R&D

- cf. history
  - Thermistors used in CMB
  - SQUIDs
- Balance enthusiasm with new direction and amount needed to get in the 100g region

Conclusions

The current combination of experiments and technologies will cover 300 MeV/c^2 to TeV/c^2.

"G2": part of the way towards neutrino floor 2020-2025

G2+: go to neutrino floor

New window below 300 MeV/c^2

Nuclear Recoils: Liquid He, Polar crystals

Electron scattering: -> keV

DM absorption:-> meV

New experimental results soon

R&D for G2/G2+ paves part the way toward those ambitious goals

Table top experiments

Exciting new ideas (cf 1985 era)

Use/manufacture low gap systems

Of course many of these clever schemes will fail, but fun

We do not need large target masses

My worries

(3.) Dark Count problem (we already see in 300 Mev/c2 to 10GeV/c2, and learn from it)

(4.) Paucity of dark matter specific signatures

Additional material

Large Improvement of Ionization

LPN HEMT (Yong Jin) 100 pf, 0.3nV/√Hz, low 1/f
=> Local amplifier at 4 K

arXiv 1611.09712v2

r.m.s.=91 eV (300pf)