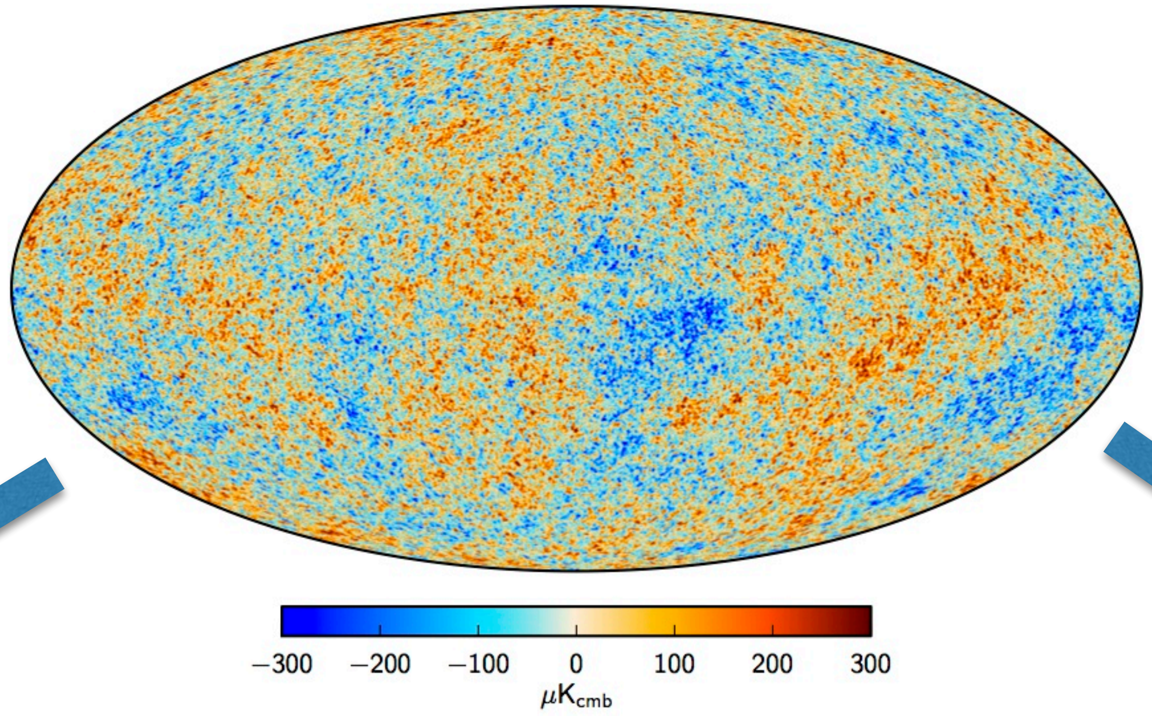
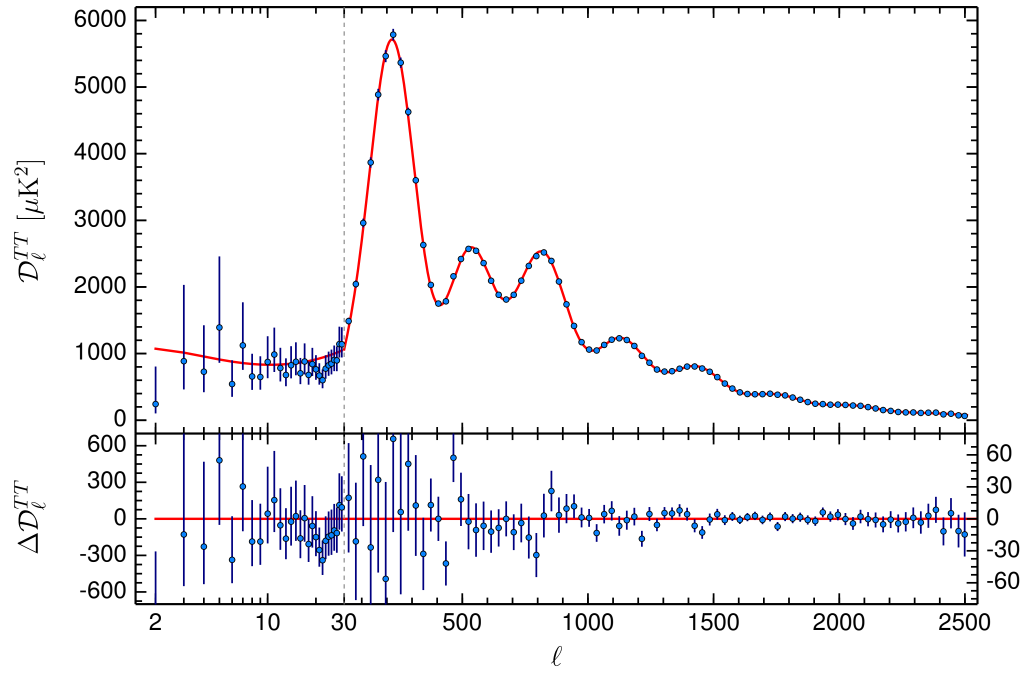
Review of recent dark matter experiments

Yoni Kahn (UIUC)

Dark matter (DM) exists!



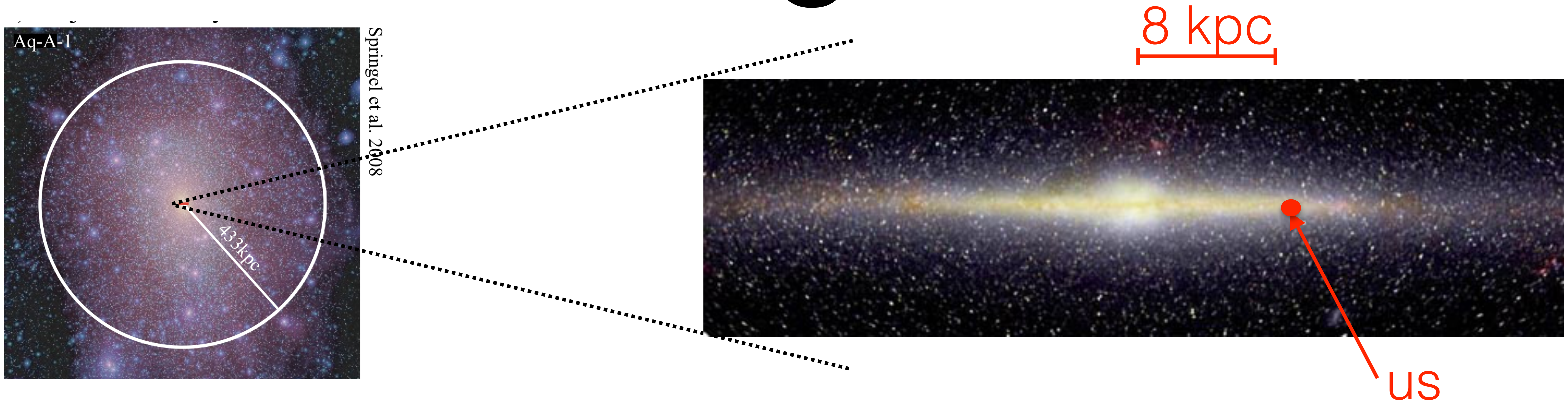


Parameter	[1] *Planck* TT+lowP
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062
H_0	67.31 ± 0.96
Ω_m	0.315 ± 0.013
σ_8	0.829 ± 0.014
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014

We have never observed a dark matter particle.

[Planck collab., A&A 2016]

DM in our neighborhood



Local measurements of stars tell us:

$$\rho_{\mathrm{DM}} \sim 0.3\ \mathrm{GeV/cm^3}$$

$$\cancel{m}_{\mathrm{DM}} v_{\mathrm{DM}}^2 \sim \cancel{m}_{\mathrm{DM}} \frac{GM(<R)}{R}$$

$$v_{\mathrm{DM}} \sim 10^{-3} c$$

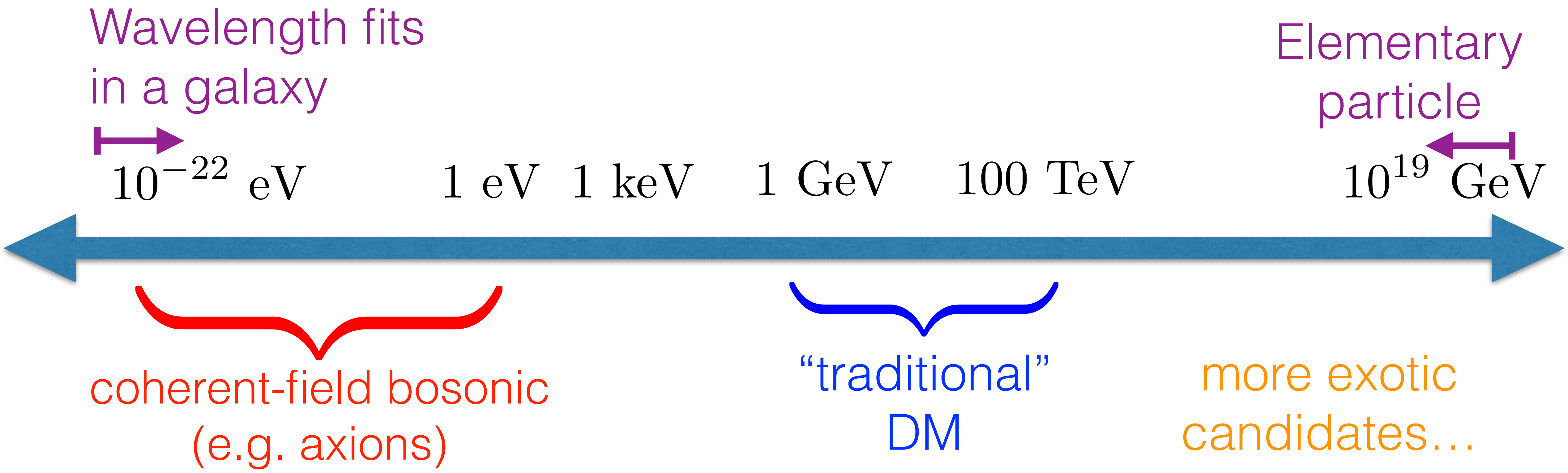
$$(\sim v_{\odot} \sim v_{\mathrm{esc}})$$

$$\rho_{\mathrm{DM}} = m_{\mathrm{DM}} \times n_{\mathrm{DM}}$$

Few heavy particles,
or lots of light particles…
what is DM mass?

[Read, J. Phys. G 2014; COBE/NASA; Springel et al. MNRAS 2008]

50 orders of magnitude!



Wavelength fits in a galaxy

Elementary particle

10^{-22} eV

1 eV

1 keV

1 GeV

100 TeV

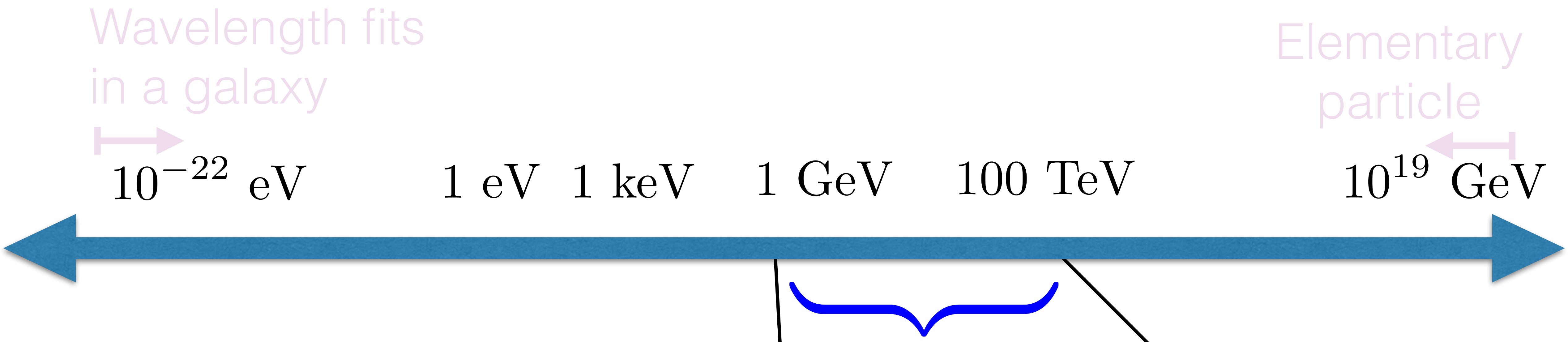
10^{19} GeV

coherent-field bosonic (e.g. axions)

“traditional” DM

more exotic candidates…

50 orders of magnitude



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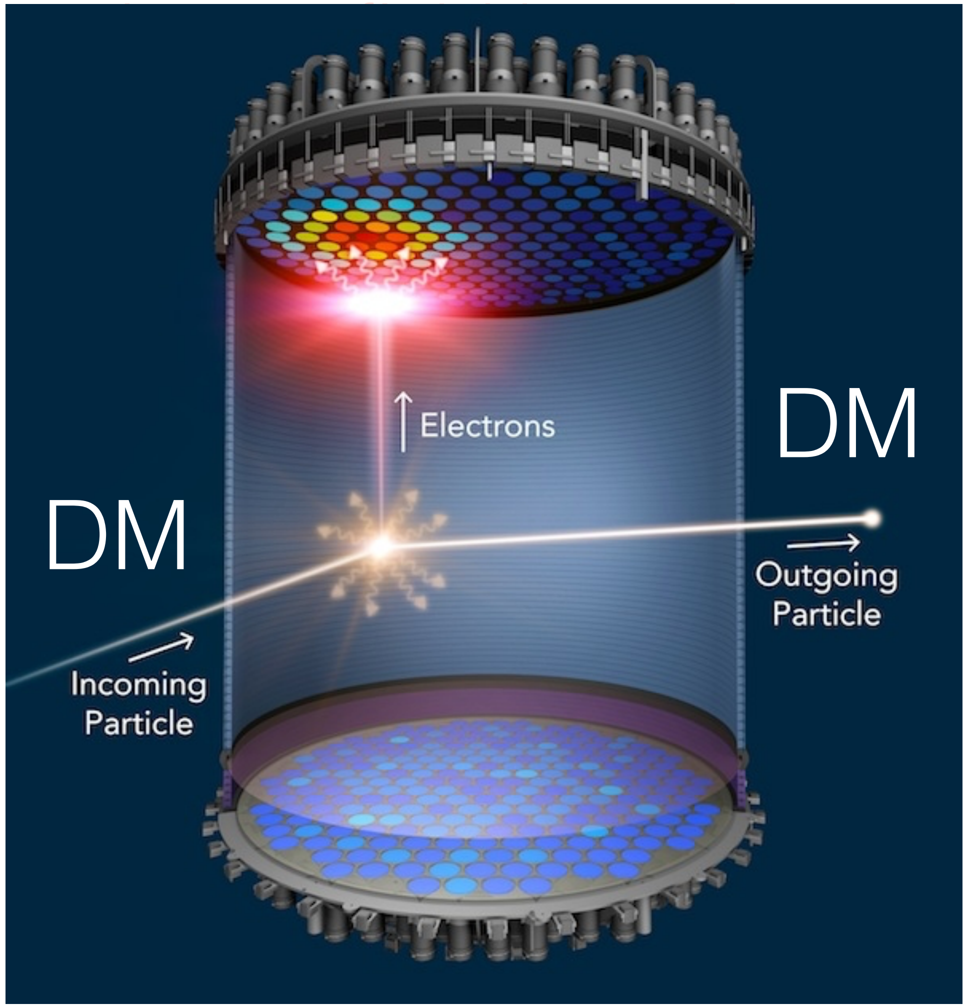


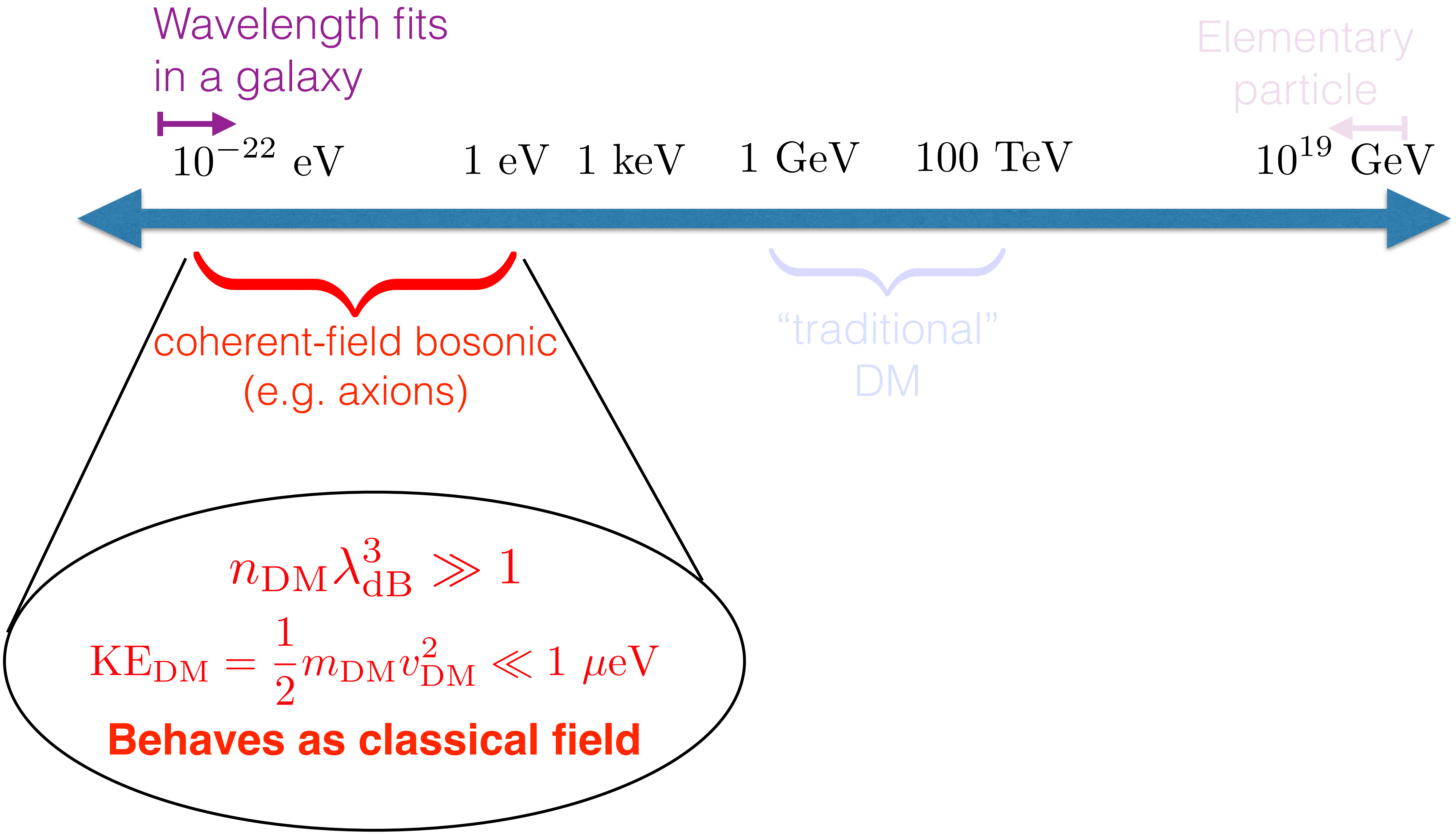
$$n_{\mathrm{DM}}\lambda_{\mathrm{dB}}^{3} \ll 1$$

$$\mathrm{KE}_{\mathrm{DM}} = \frac{1}{2}m_{\mathrm{DM}}v_{\mathrm{DM}}^{2} > 1\ \mathrm{keV}$$

Rare collisions

[Goodman & Witten PRD 1985; Drukier, Freese, Spergel PRD 1986; image credit LZ collab.]

50 orders of magnitude



$$n_{\mathrm{DM}}\lambda_{\mathrm{dB}}^{3} \gg 1$$

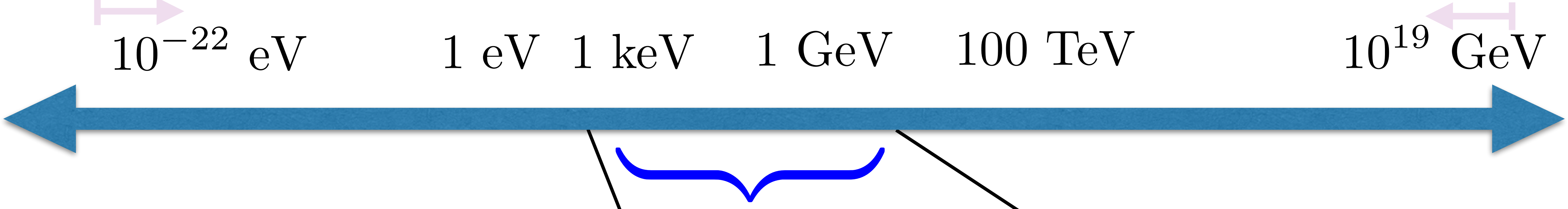
$$\mathrm{KE}_{\mathrm{DM}} = \frac{1}{2}m_{\mathrm{DM}}v_{\mathrm{DM}}^{2} \ll 1\ \mu\mathrm{eV}$$

Behaves as classical field

50 orders of magnitude

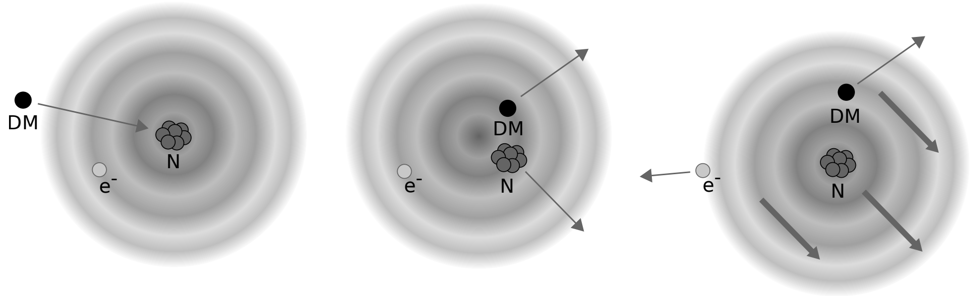
Wavelength fits in a galaxy

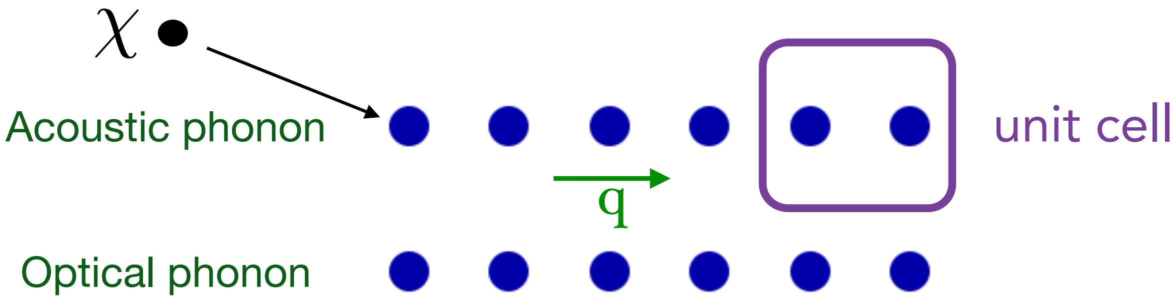
Elementary particle



10^{-22} eV 1 eV 1 keV 1 GeV 100 TeV 10^{19} GeV

sub-GeV DM





$$n_{\mathrm{DM}}\lambda_{\mathrm{dB}}^{3} \ll 1$$

$$\mathrm{KE}_{\mathrm{DM}} \sim 10\ \mathrm{meV} - 1\ \mathrm{keV}$$

Not-so-rare collisions, need low thresholds

[Essig, Mardon, Volansky PRD 2012; Knapen, Lin, Pyle, Zurek, PLB 2018; Dolan, Kahlhoefer, McCabe PRL 2018; Ibe et al. JHEP 2018]

Axion DM experiments

Axion DM Theory

$$a(\mathbf{x},t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a}\cos(m_a t + \mathcal{O}(v_{\mathrm{DM}})\mathbf{x})$$

amplitude set
by local DM density

oscillates at frequency
set by DM mass

e.g. $m_a = 10^{-9}$ eV

$\lambda_{\mathrm{Comp}} \sim$ km

$\tau_{\mathrm{Comp}} \sim \mu\mathrm{s}$

Local DM velocity → Spatial coherence → Temporal coherence

$$\Delta v_{\mathrm{DM}} \sim v_{\mathrm{DM}} \sim 10^{-3}$$

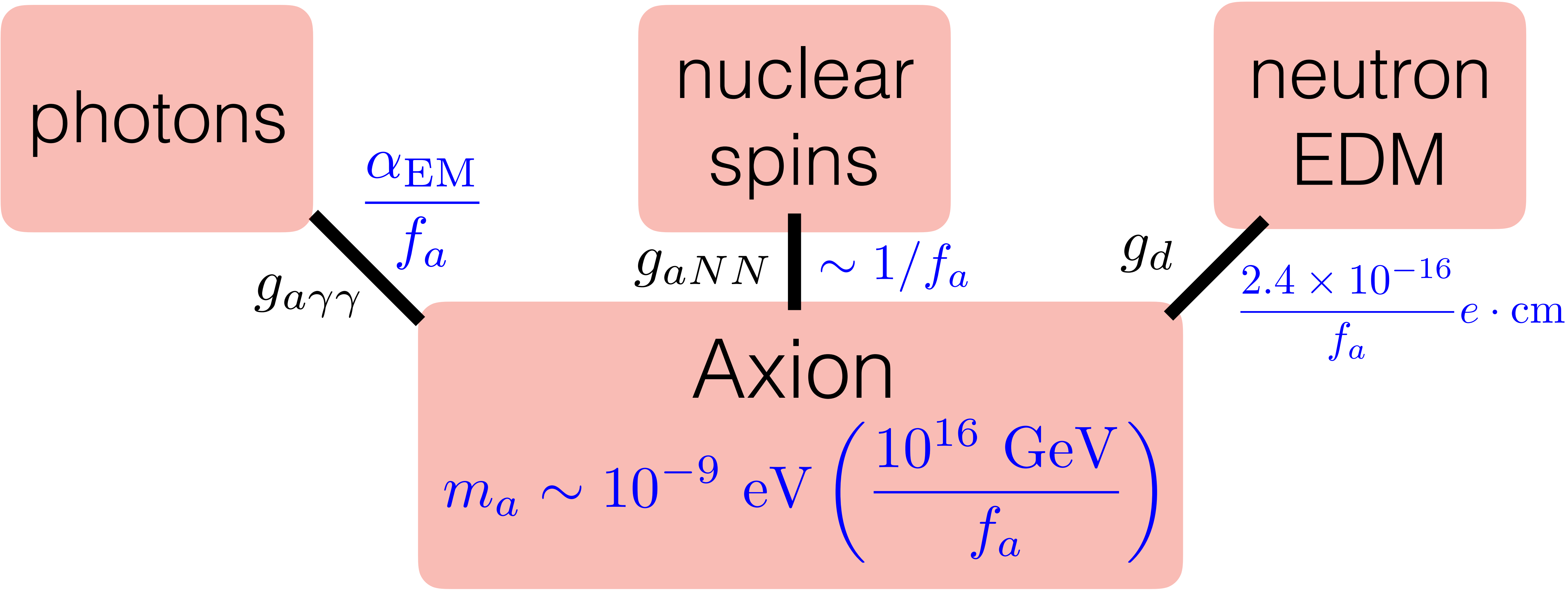
$$\lambda_{\mathrm{dB}} = \frac{\lambda_{\mathrm{Comp}}}{v_{\mathrm{DM}}}$$

$$\tau_{\mathrm{coh}} = \frac{\tau_{\mathrm{Comp}}}{v_{\mathrm{DM}}^2}$$

Classical physics is fine: $m_a = 10^{-9}\ \mathrm{eV} \implies N_a \sim 10^{18}/\mathrm{cm}^3$

[Graham and Rajendran, PRD 2013]

How do axions interact?



photons

nuclear spins

neutron EDM

$g_{a\gamma\gamma}$ $\frac{\alpha_{\mathrm{EM}}}{f_a}$

g_{aNN} $\sim 1/f_a$

g_d $\frac{2.4 \times 10^{-16}}{f_a} e \cdot \mathrm{cm}$

Axion

$$m_a \sim 10^{-9}\ \mathrm{eV} \left(\frac{10^{16}\ \mathrm{GeV}}{f_a}\right)$$

For QCD axion, only one free parameter!

While strong-CP is a great motivation, let’s think broadly.
For this talk, “axion” can vary mass/coupling relation

[Graham and Rajendran, PRD 2013]

What should we measure?

$$a(\mathbf{x},t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a}\cos(m_a t + \mathcal{O}(v_{\mathrm{DM}})\mathbf{x})$$

In axion DM background, get oscillating observables:

$$\left.\begin{aligned}\nabla \times \mathbf{B}_a &= \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma\gamma}\left(\mathbf{E}_0 \times \nabla a - \mathbf{B}_0 \frac{\partial a}{\partial t}\right) \\ \nabla \cdot \mathbf{E}_a &= -g_{a\gamma\gamma}\mathbf{B}_0 \cdot \nabla a\end{aligned}\right\}$$

Oscillating response from static fields

$$H_N \supset g_{aNN} \nabla a \cdot \vec{\sigma}_N$$

Spin-dependent force

$$d_n = g_d a$$

Time-varying EDM

Note: $\nabla a \sim v_{\mathrm{DM}} \sim 10^{-3}$ so some are easier than others

[Sikivie, PRL 1983]

Axion searches with magnetic fields

$$\underbrace{\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t}} - g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Cavity regime: $\lambda_{\mathrm{Comp}} \sim R_{\mathrm{exp}}$

e.g. ADMX

$$\nabla \times \mathbf{B}_a = \cancel{\frac{\partial \mathbf{E}_a}{\partial t}} \underbrace{- g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}_{\mathbf{J}_{\mathrm{eff}}}$$

Quasistatic regime: $\lambda_{\mathrm{Comp}} \gg R_{\mathrm{exp}}$

e.g. ABRACADBRA

$$\cancel{\nabla \times \mathbf{B}_a} = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

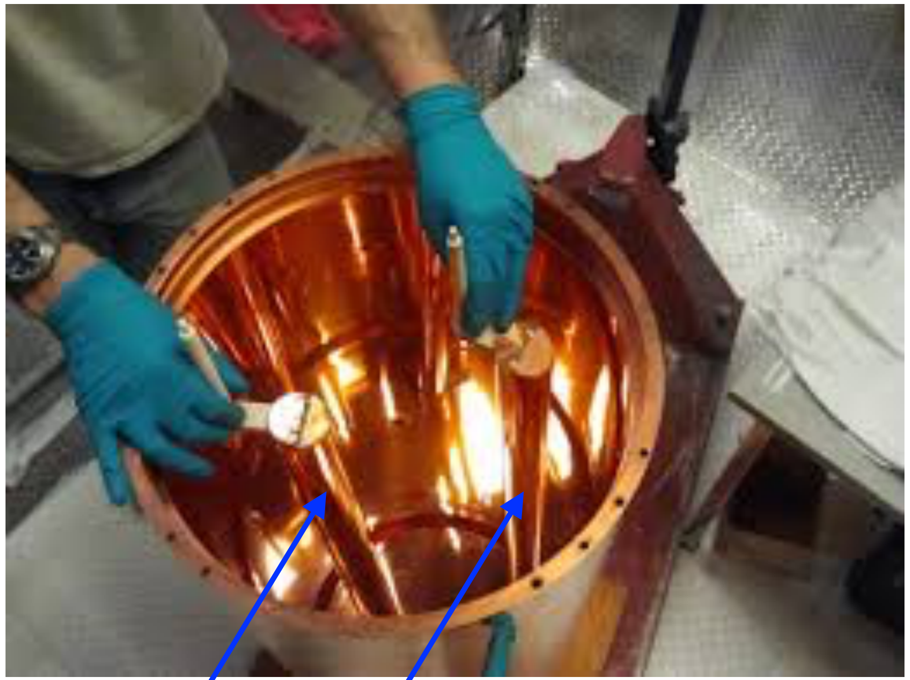
Radiation regime: $\lambda_{\mathrm{Comp}} \ll R_{\mathrm{exp}}$

e.g. MADMAX

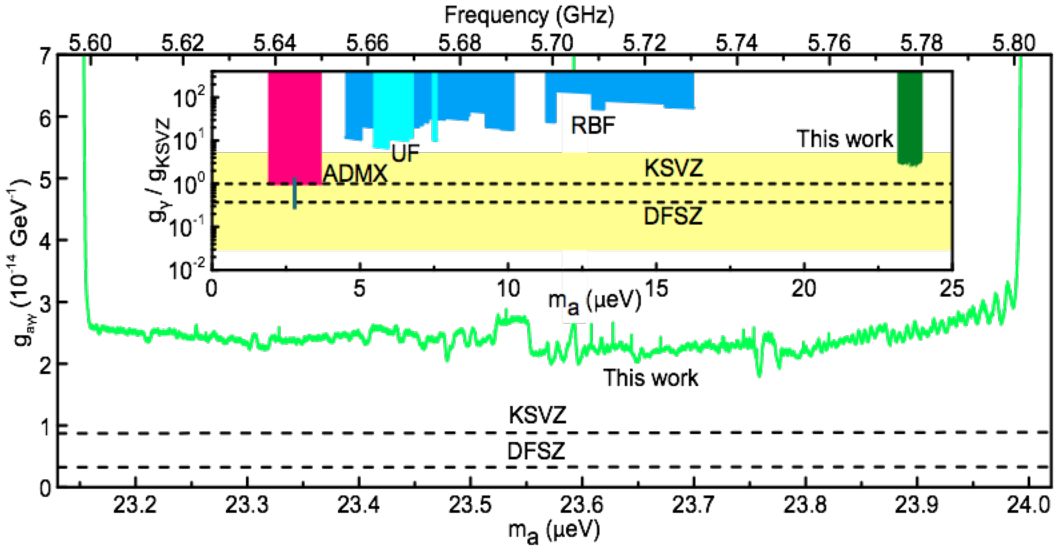
Resonant cavity detection

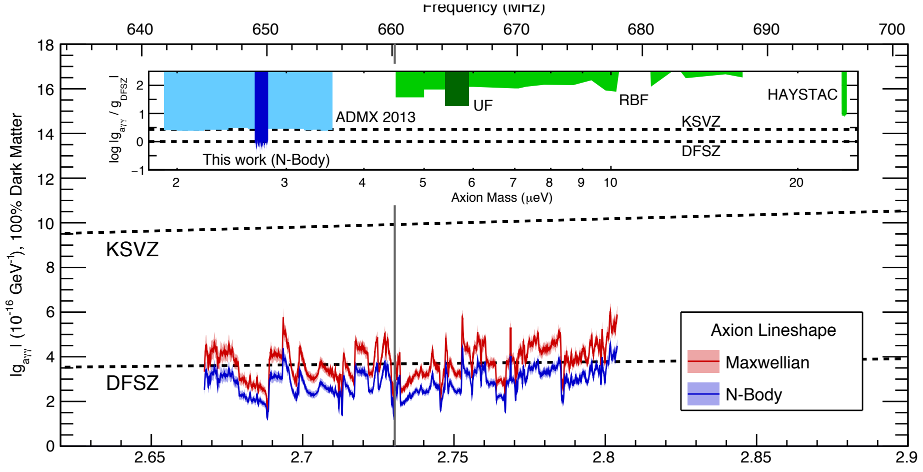
$$\underbrace{\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t}}_{\text{cavity response}} \underset{\text{axion source}}{- g_{a\gamma\gamma} \mathbf{B}_0 \frac{\partial a}{\partial t}}$$

$$P \sim g_{a\gamma\gamma}^2 \frac{\rho_{\rm DM}}{m_a} B_0^2 V Q$$



Tune cavity modes
to scan axion masses



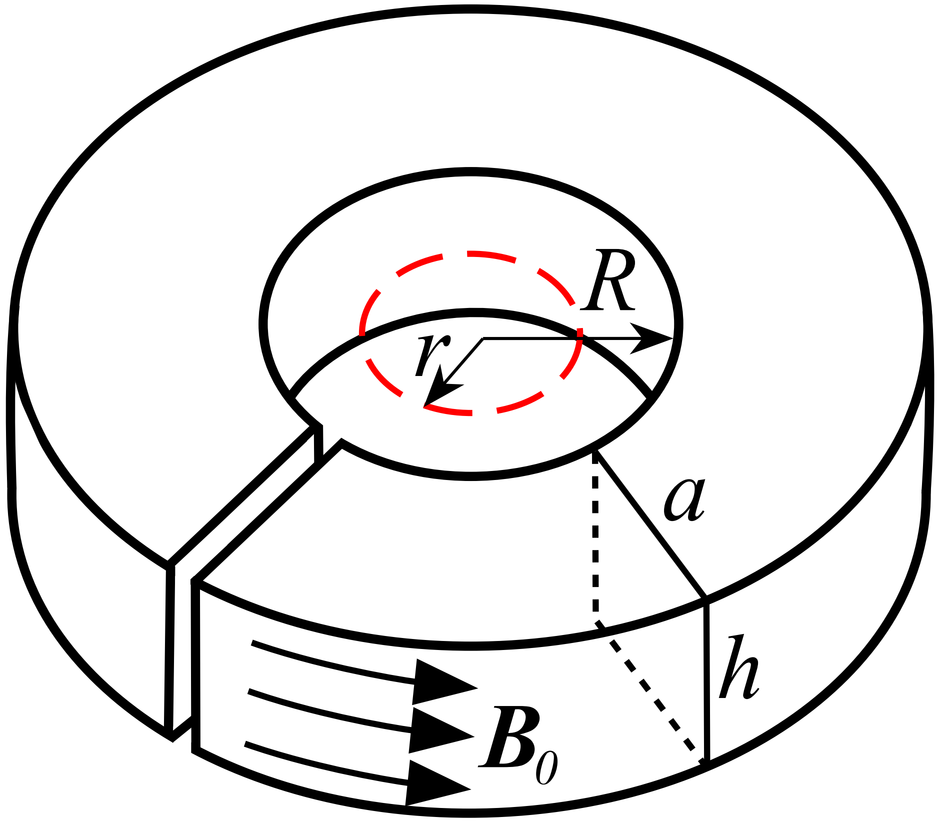


Cavity b.c. fix mass range to cavity size;
larger masses -> smaller V

[HAYSTAC PRD 2018, ADMX PRL 2018]

Quasistatic regime: ABRACADABRA

A **B**roadband/**R**esonant **A**pproach to **C**osmic **A**xion **D**etection
with an **A**mplifying **B**-field **R**ing **A**pparatus



[**YK**, Safdi, Thaler, PRL 2016]

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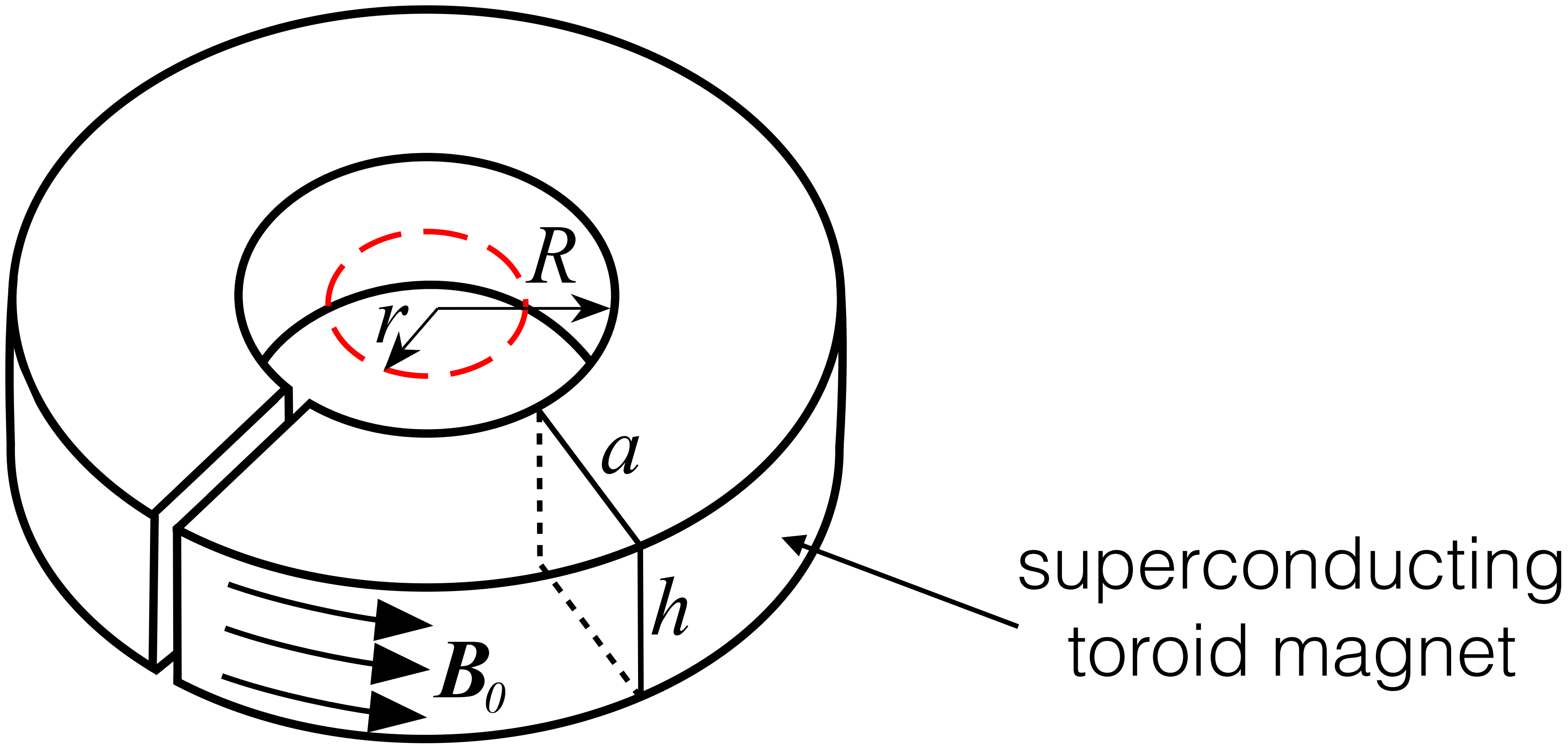

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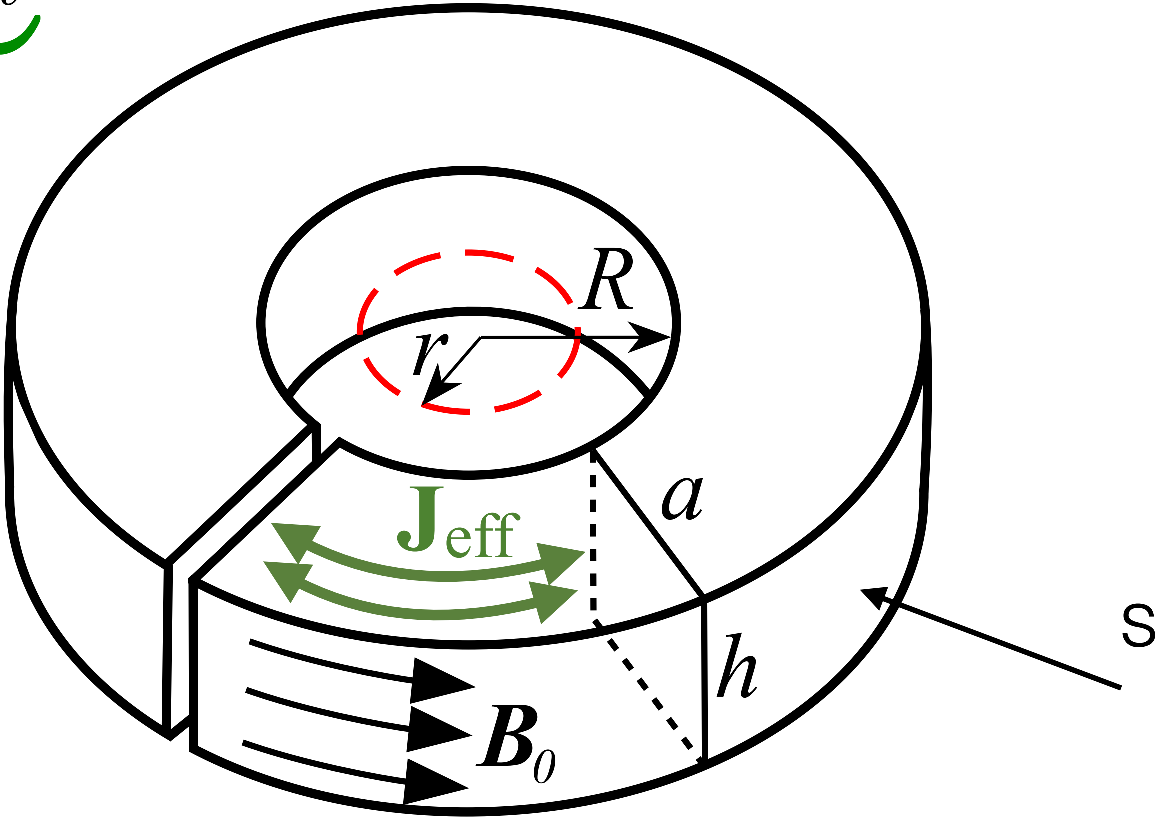

superconducting
toroid magnet

[**YK**, Safdi, Thaler, PRL 2016]

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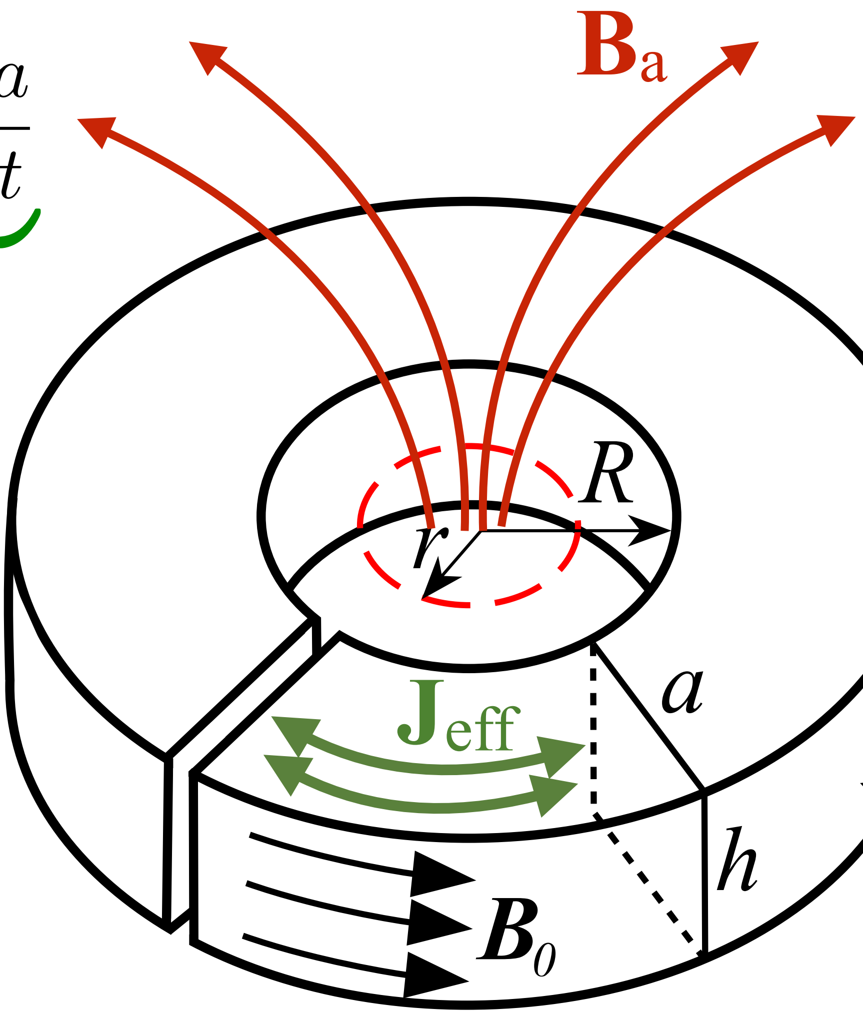

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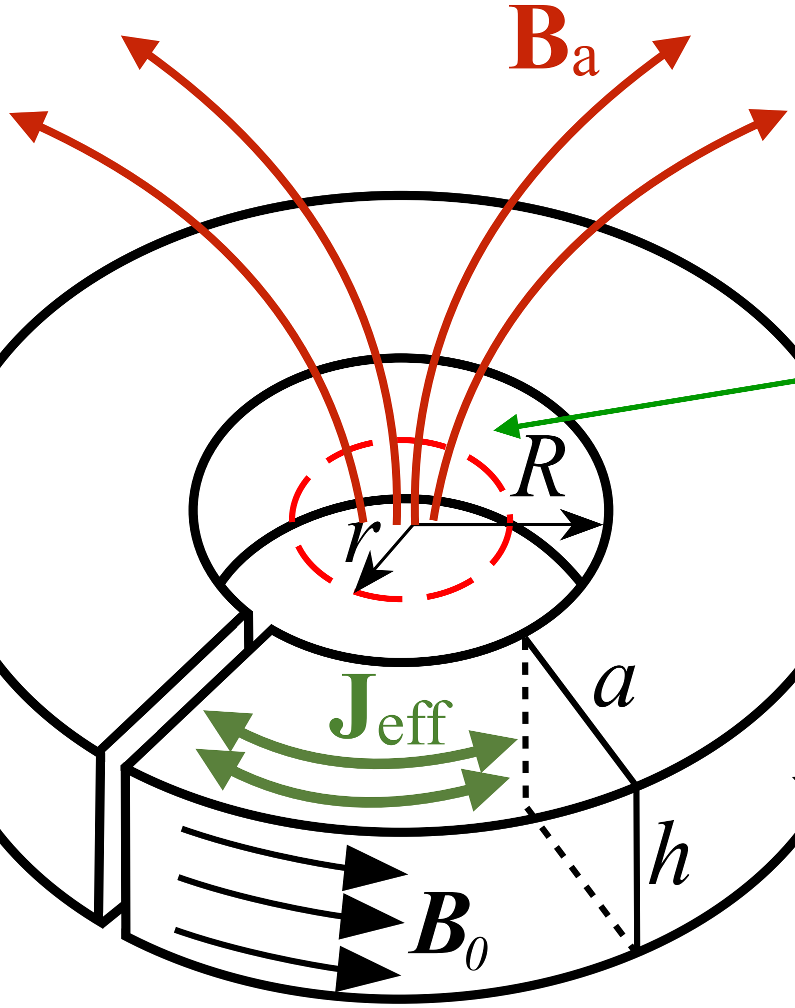

broadband or resonant detection in **zero-field** region

superconducting toroid magnet

[**YK**, Safdi, Thaler, PRL 2016]

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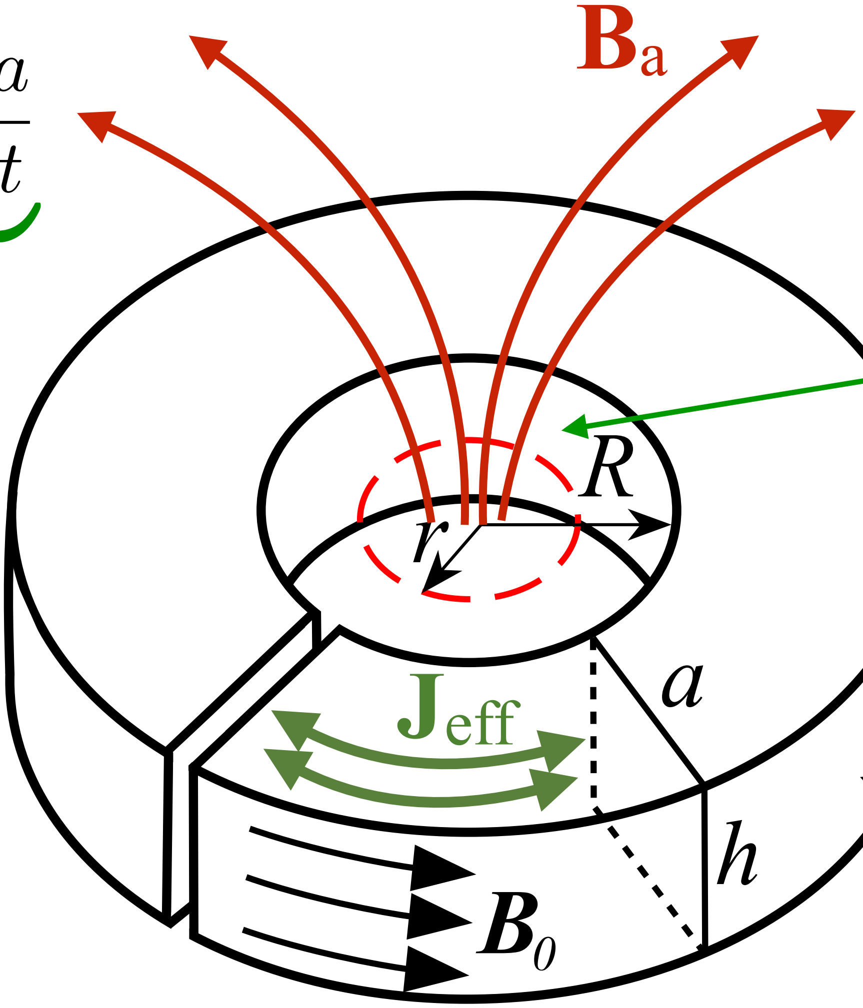


broadband or resonant detection in **zero-field** region

superconducting toroid magnet

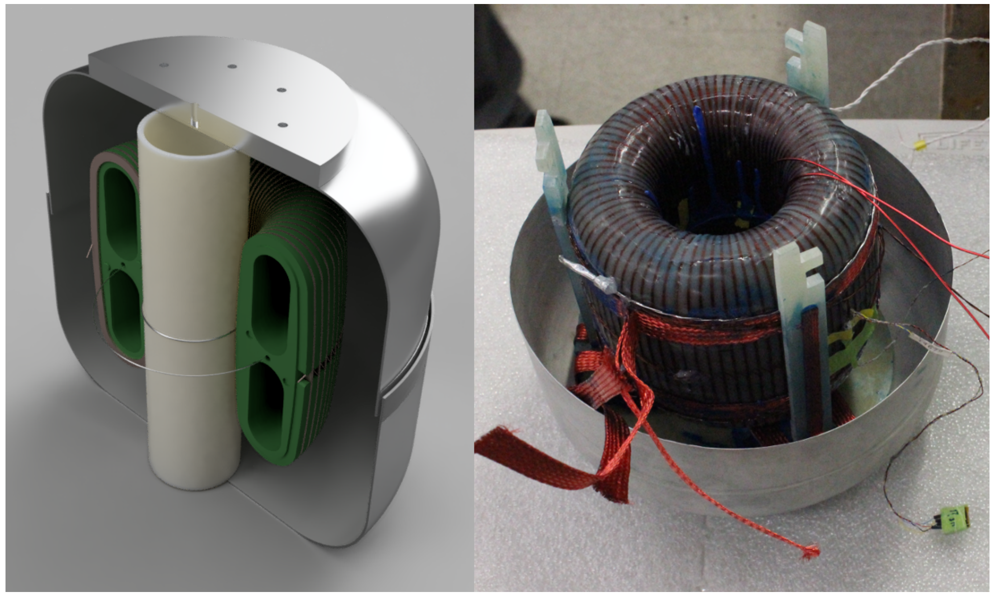
$$\langle \Phi(t)^2 \rangle \sim g_{a\gamma\gamma}^2 \rho_{\mathrm{DM}} B_0^2 V^{5/3}$$

Volume enhancement at low masses

[**YK**, Safdi, Thaler, PRL 2016]

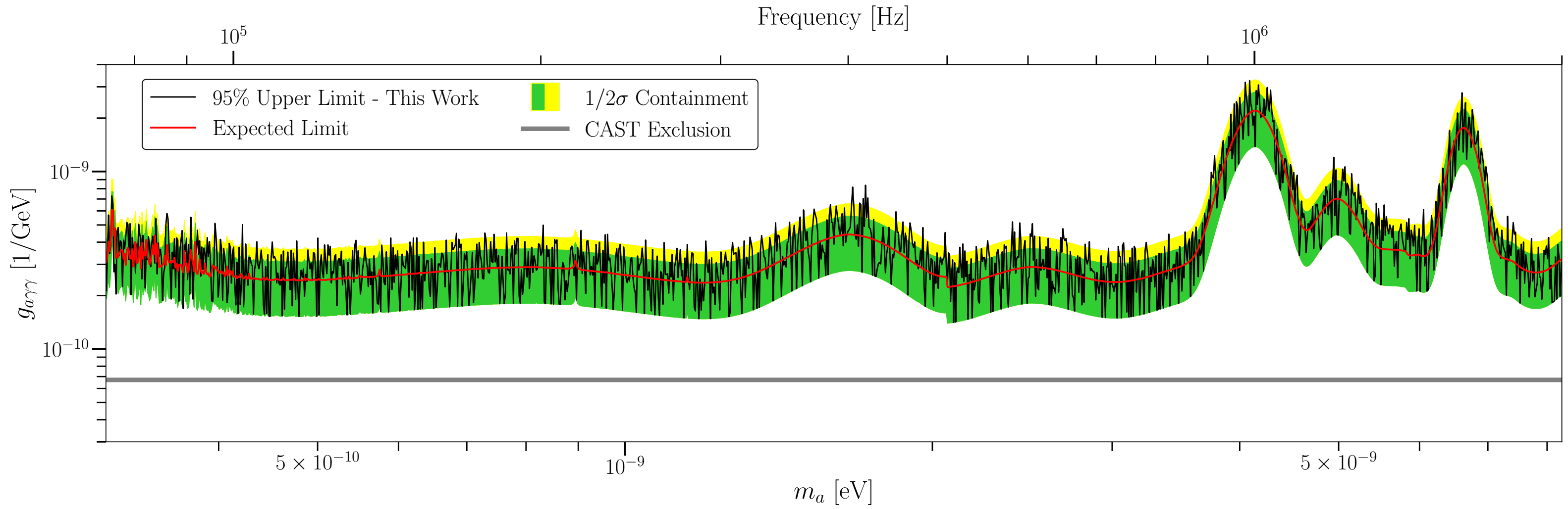
ABRACADABRA

first results



10 cm magnet and pickup

inside a 150 mK
dilution refrigerator



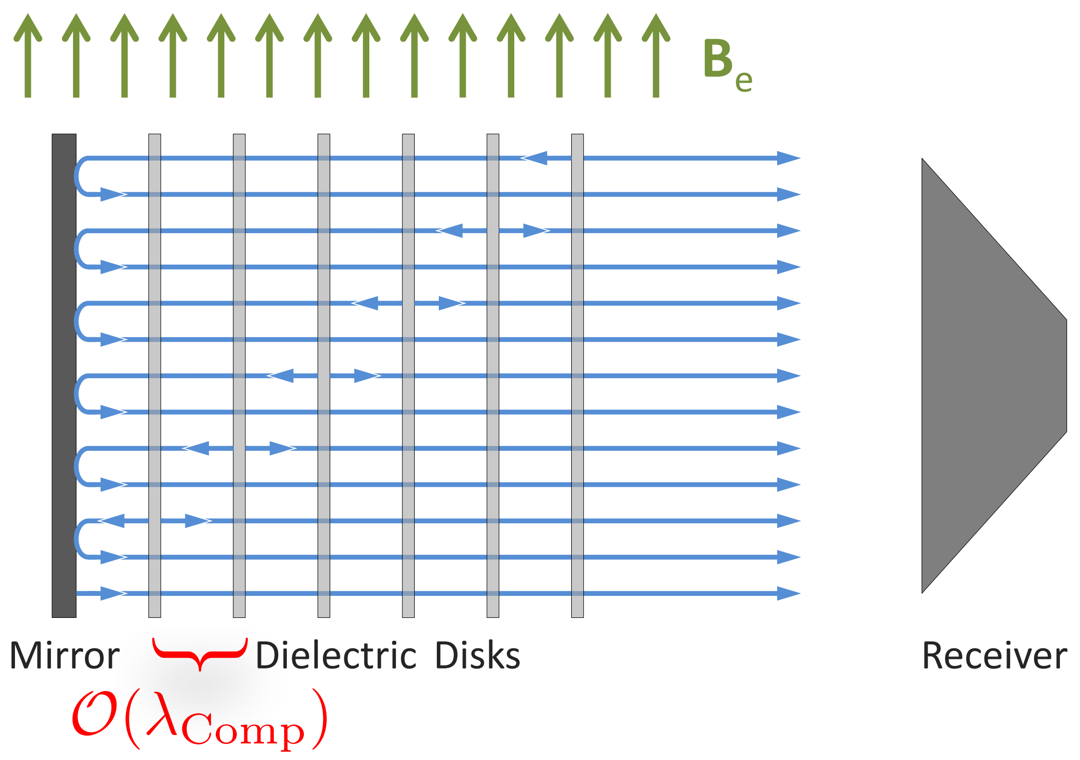
Second run underway, expect better limits soon;
merging w/DM-Radio @ SLAC

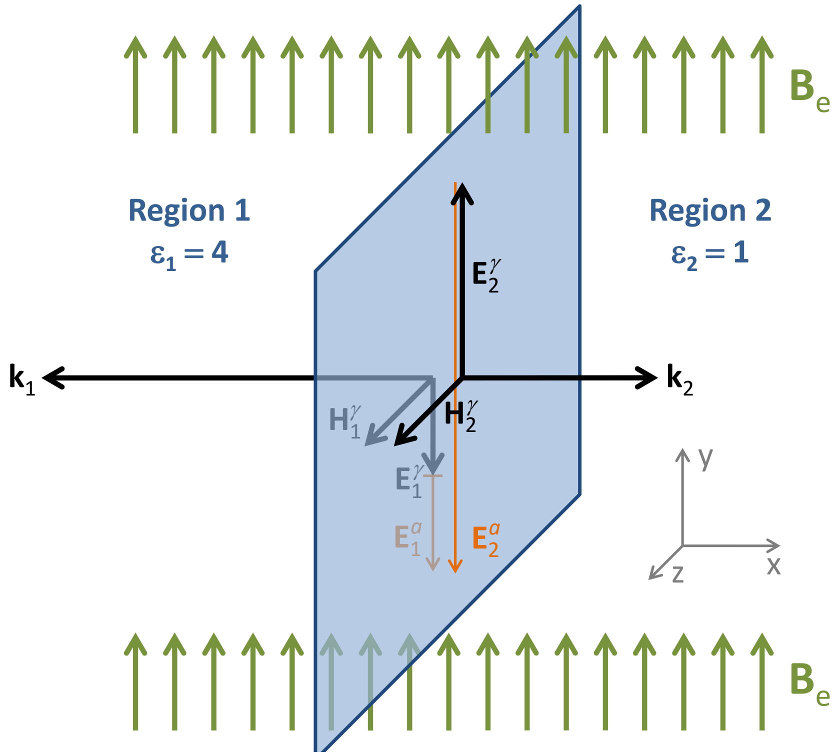
[Ouellet, **YK**, Winslow, et al., PRL 2019; PRD 2019]

Radiation regime: MADMAX

$$\nabla \times \cancel{\mathbf{B}_a} = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma\gamma}\mathbf{B}_0\frac{\partial a}{\partial t} \Longrightarrow \mathbf{D}_a(t) = \epsilon\mathbf{E}_a(t) = -g_{a\gamma\gamma}\mathbf{B}_0 a(t)$$

E+M boundary condition at interfaces forces radiation to cancel axion-induced **D**





Composite design with large volume and high Q, design underway

[Millar et al. JCAP 2017, MADMAX working group PRL 2017]

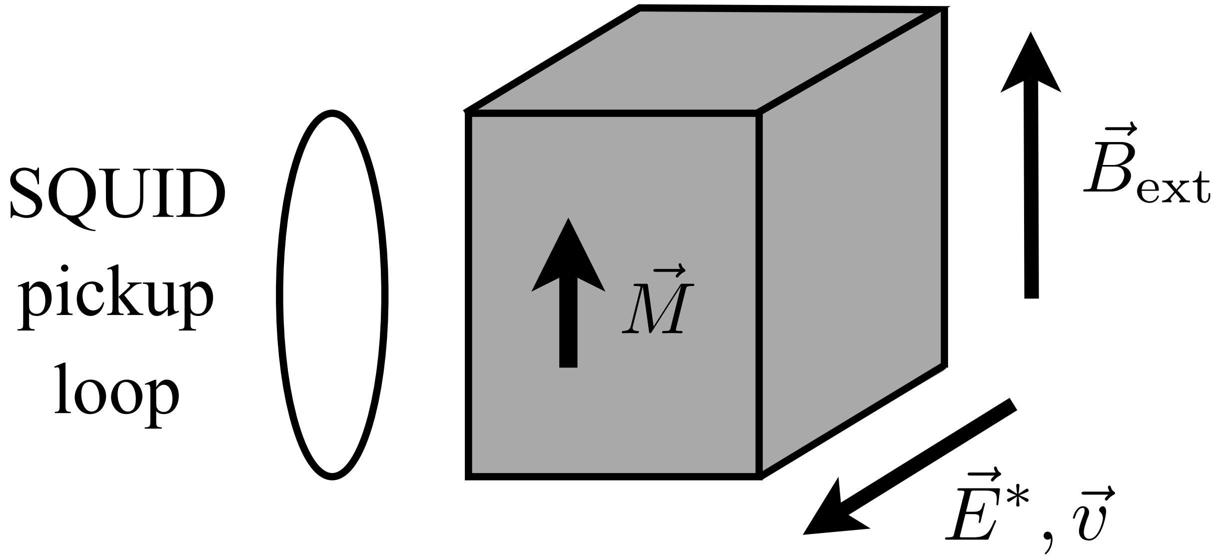
NMR with axion DM

Nuclei immersed in axion DM can have:

Oscillating EDM and/or Spin-dependent force

$$d_n = g_d \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a} \cos(m_a t)$$

$$H_N \supset g_{aNN} \sqrt{2\rho_{DM}} \cos(m_a t)\vec{v} \cdot \vec{\sigma}_N$$



[Budker et al., Phys. Rev. X 2014; Graham and Rajendran, Phys. Rev. D 2013]

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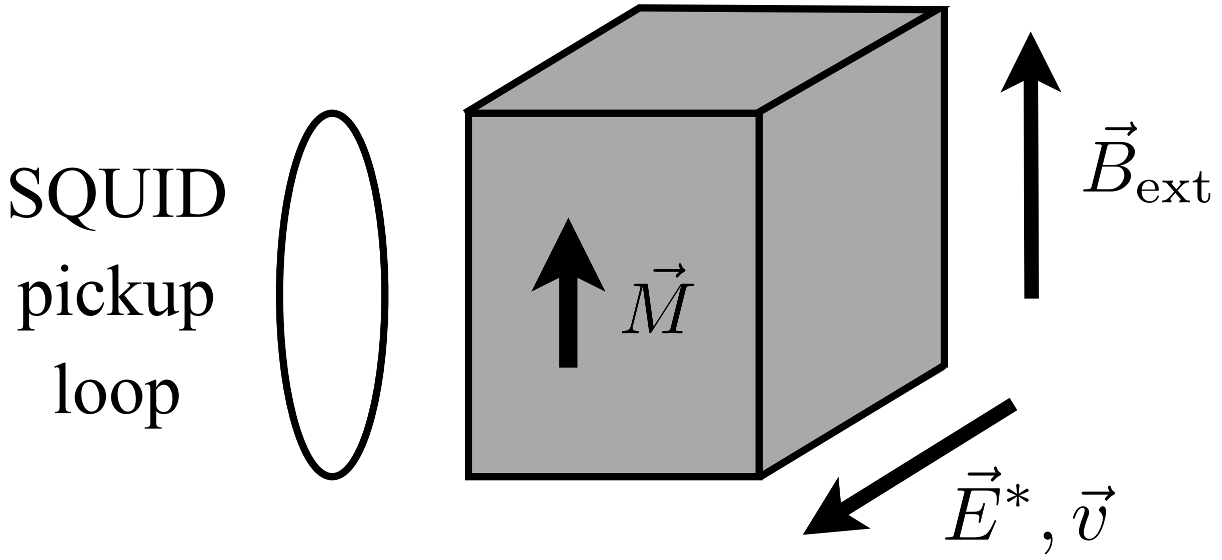
Polarize some spins, watch them precess around:

External E field and/or Axion field velocity



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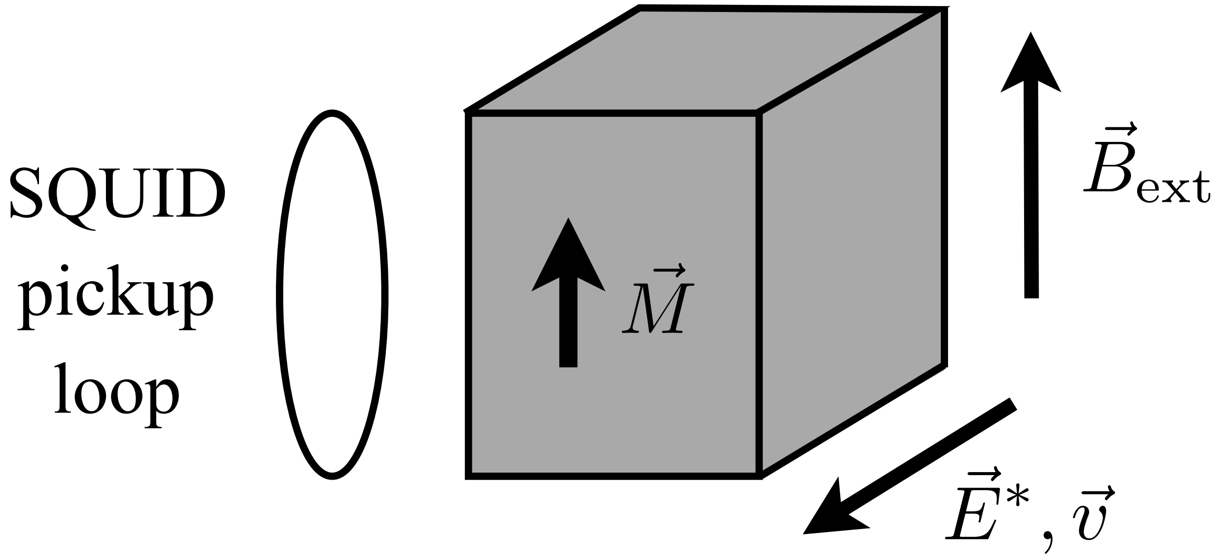


Axion DM is like NMR pulse

Resonance in transverse magnetization when $2\mu B_{\mathrm{ext}} = m_a$

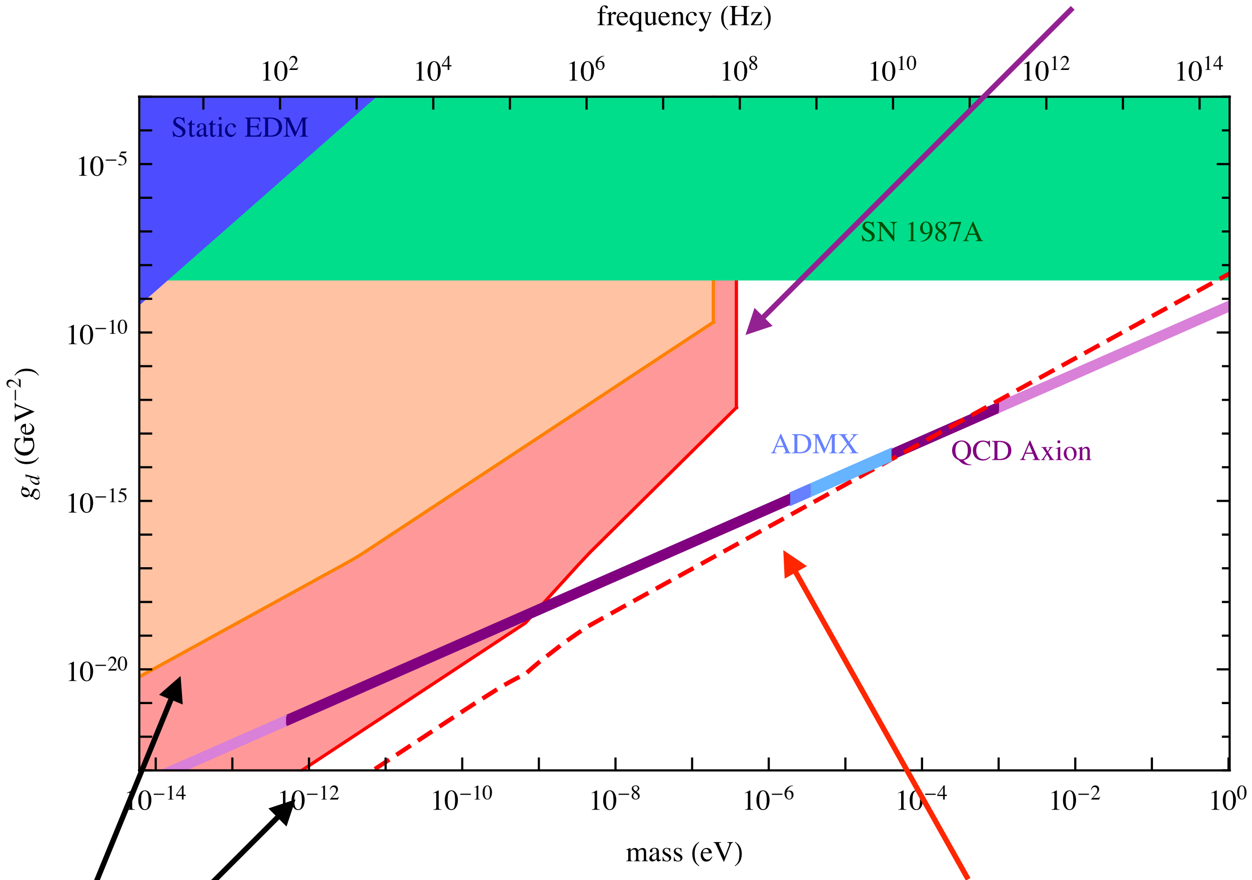
[Budker et al., Phys. Rev. X 2014; Graham and Rajendran, Phys. Rev. D 2013]

CASPEr projected Reach

CASPEr-Electric

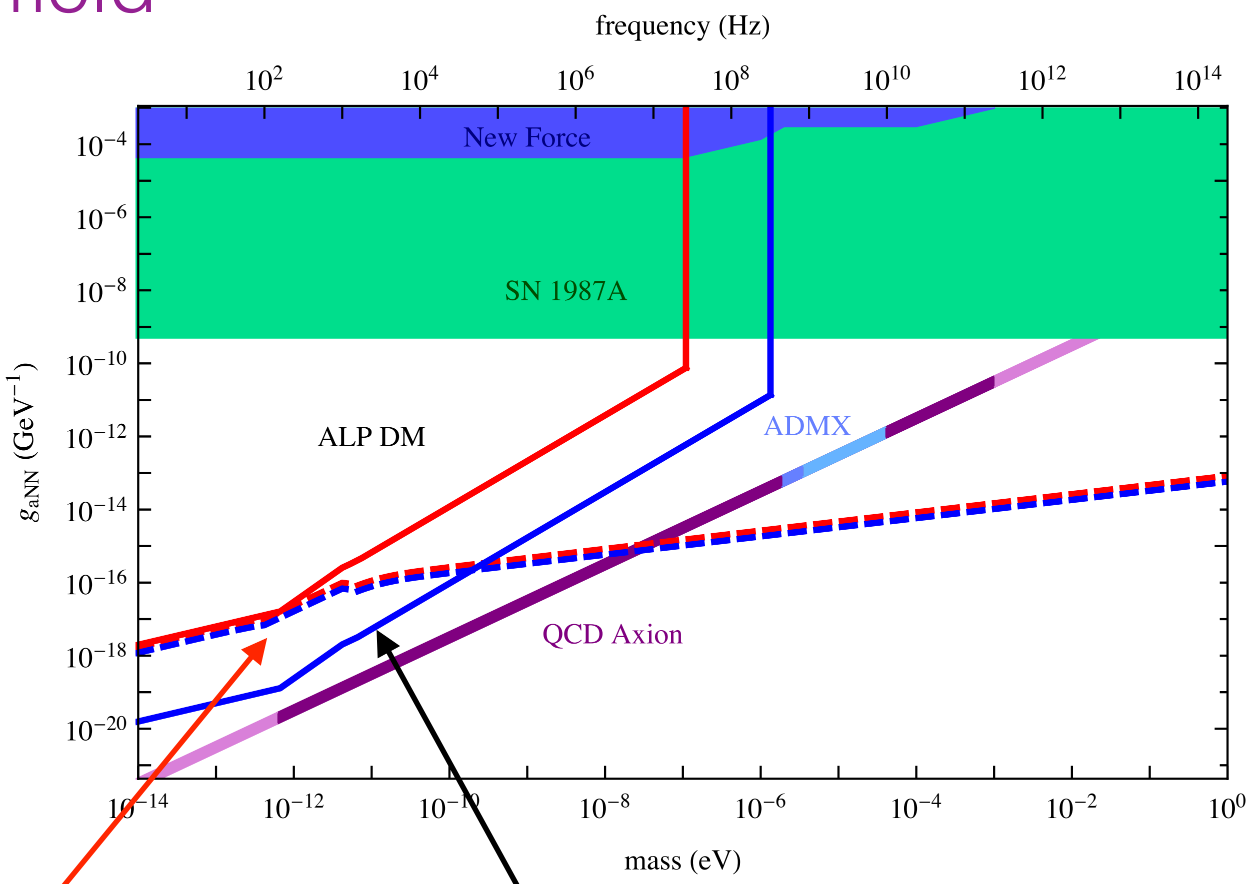
[Budker et al., Phys. Rev. X 2014]

20 T max B-field



CASPEr-Wind

[Graham and Rajendran, Phys. Rev. D 2013]



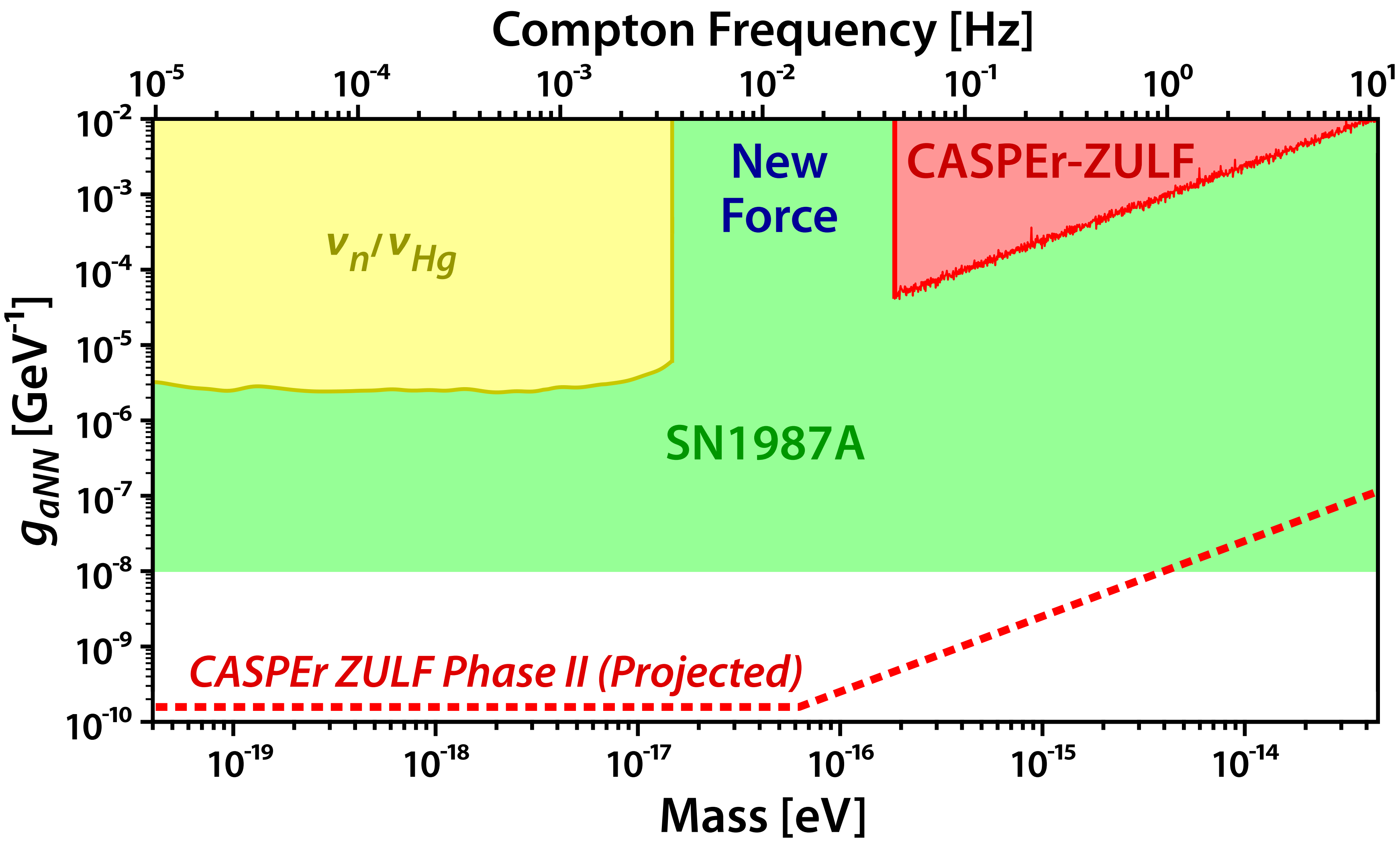
magnetization noise

non-decoupling signal!

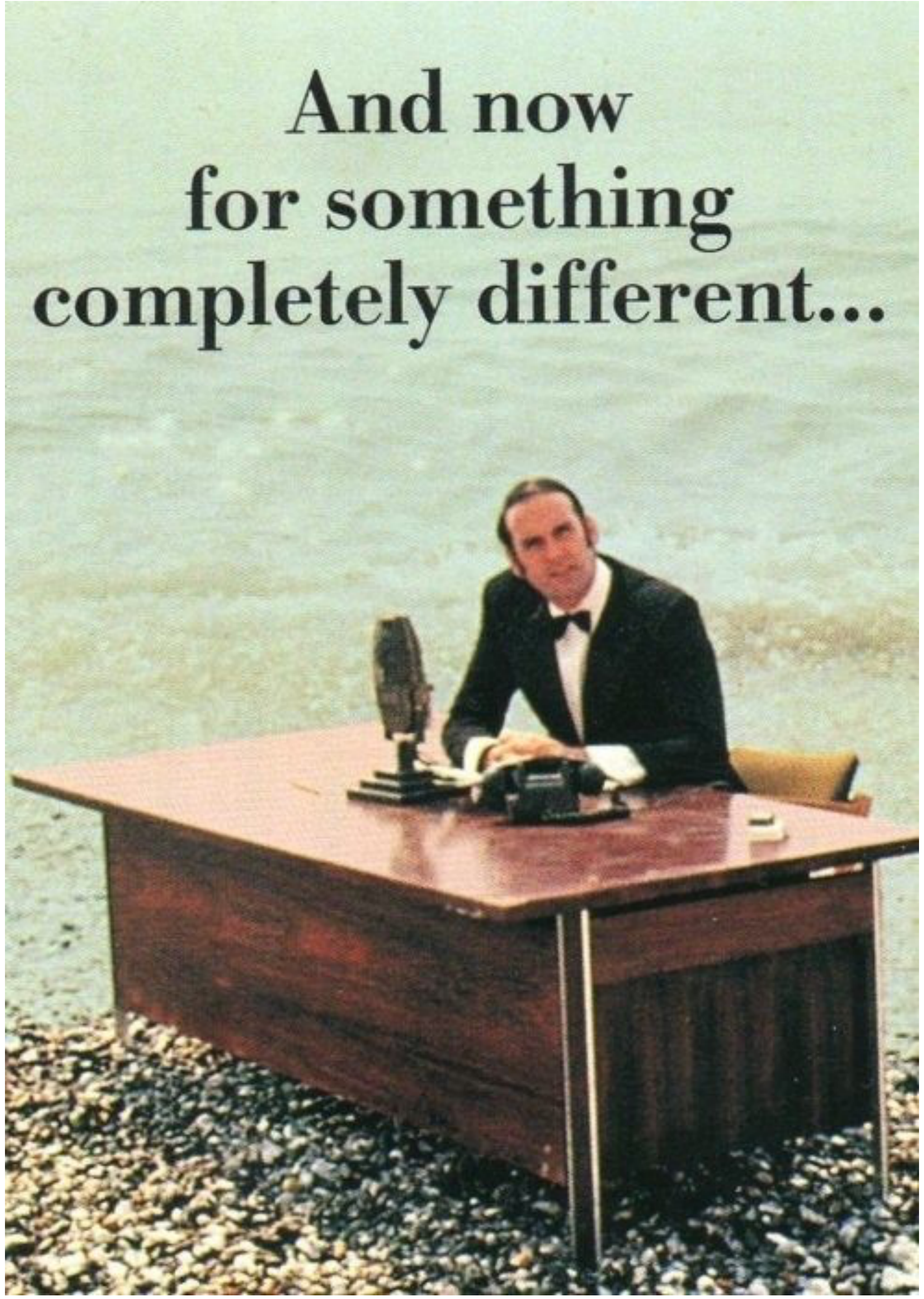
velocity suppression:
can't quite reach QCD axion

CASPEr ZULF

ALP Wind coupling at very low frequencies



[Garcon et al., Science Advances 2019]



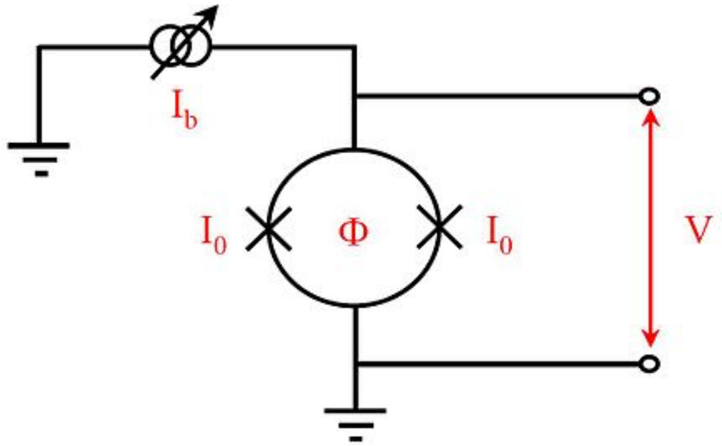
Some musings on direct detection

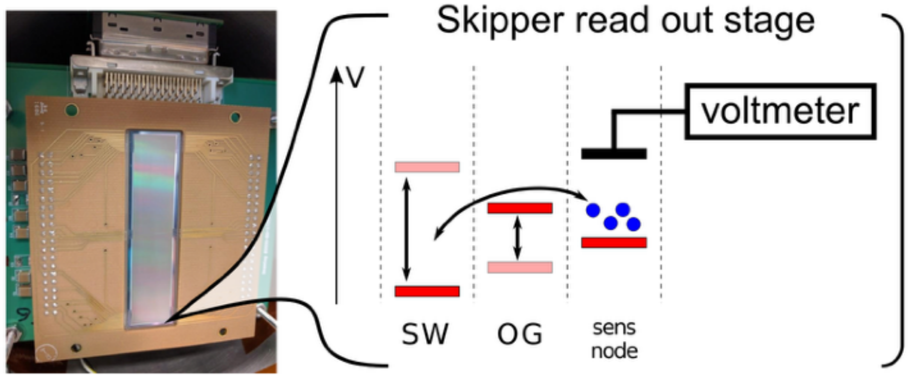
w/N. Kurinsky, D. Baxter, G. Krnjaic

Direct detection principles

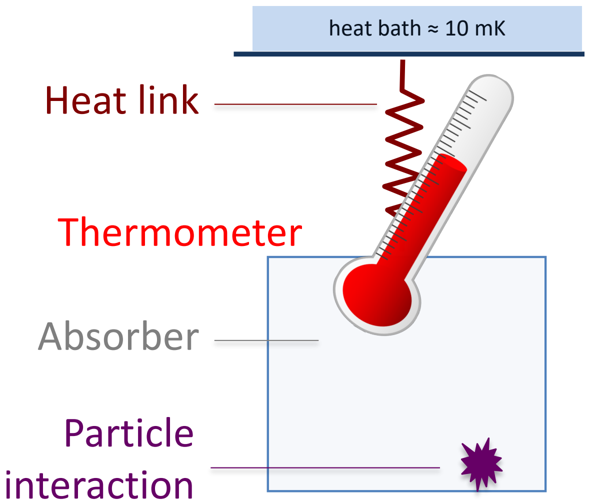
Three things detectors can see: charge, light, and heat

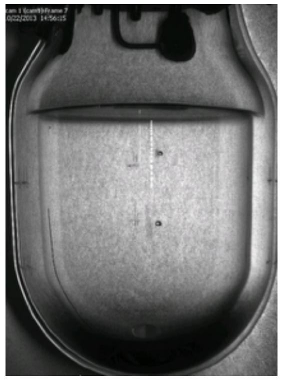
Charge: measure current
(e.g. SQUID + HEMT)
or voltage (e.g. CCD)



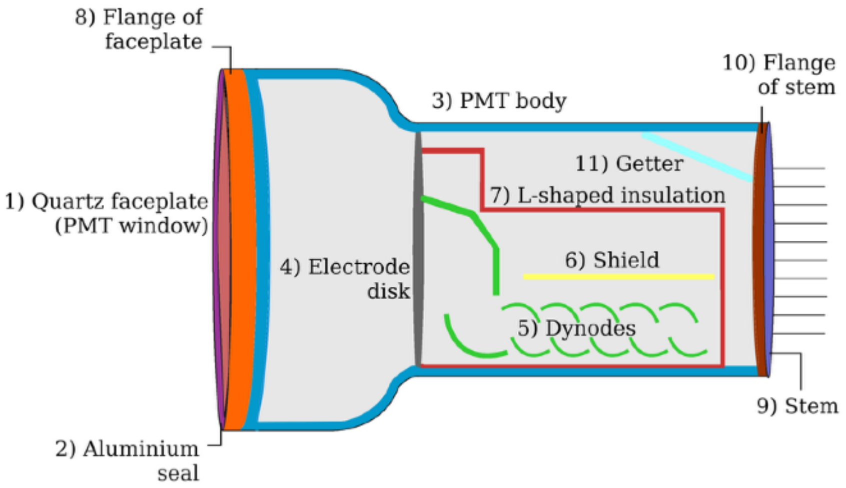


Heat: bolometer
(e.g. TES, MKID)
or bubble chamber





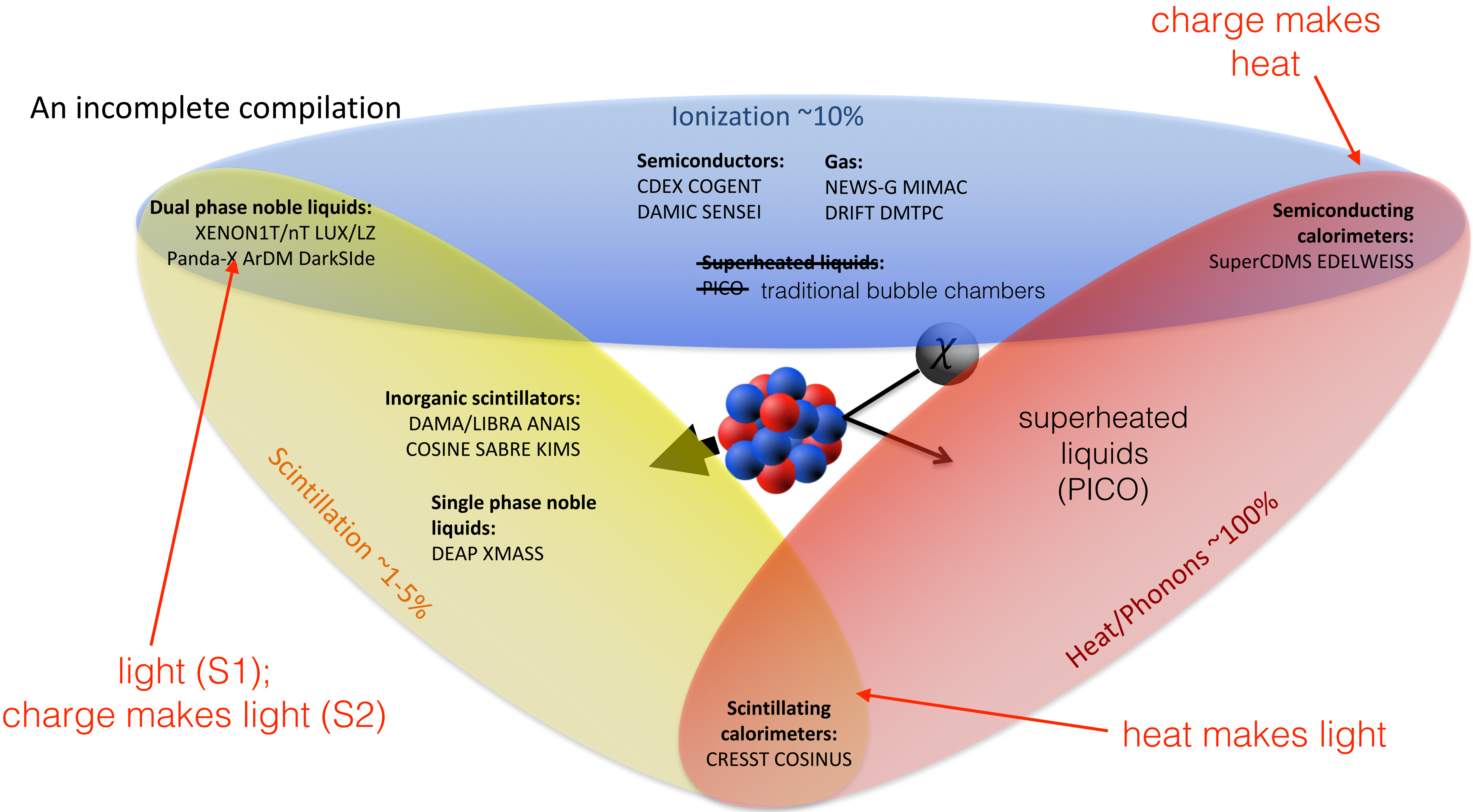
Light: photosensor
(e.g. PMT)



(but really, charge makes
light and light makes
charge so these are interchangeable:
e.g. SiPM is a “photodetector”
but triggers on e/h pairs)

The dictionary is complicated!

An incomplete compilation



Ionization ~10%

Semiconductors:
CDEX COGENT
DAMIC SENSEI

Gas:
NEWS-G MIMAC
DRIFT DMTPC

~~**Superheated liquids:**~~
~~PICO~~ traditional bubble chambers

Dual phase noble liquids:
XENON1T/nT LUX/LZ
Panda-X ArDM DarkSIde

Semiconducting calorimeters:
SuperCDMS EDELWEISS

charge makes heat

Inorganic scintillators:
DAMA/LIBRA ANAIS
COSINE SABRE KIMS

Single phase noble liquids:
DEAP XMASS

superheated liquids (PICO)

Scintillation ~1-5%

Heat/Phonons ~100%

light (S1);
charge makes light (S2)

Scintillating calorimeters:
CRESST COSINUS

heat makes light

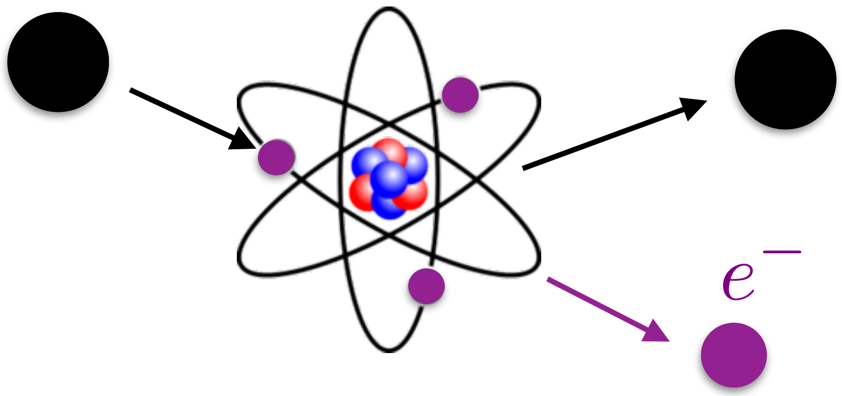
For traditional WIMP DM, signals and mapping between primary event and end-stage signal well-calibrated. For light DM and low thresholds, not so much!

[Figure courtesy F. Petricca]

More than just nuclear recoil!

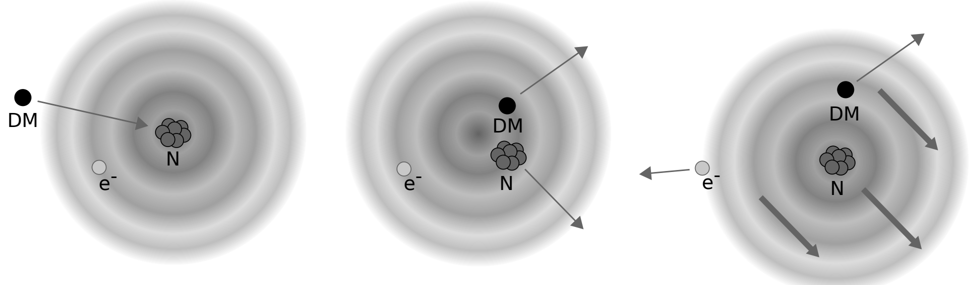
An isolated atom (nucleus + electrons) at rest is a momentum and energy eigenstate. If you whack the atom, both recoil

If you hit the electron directly:

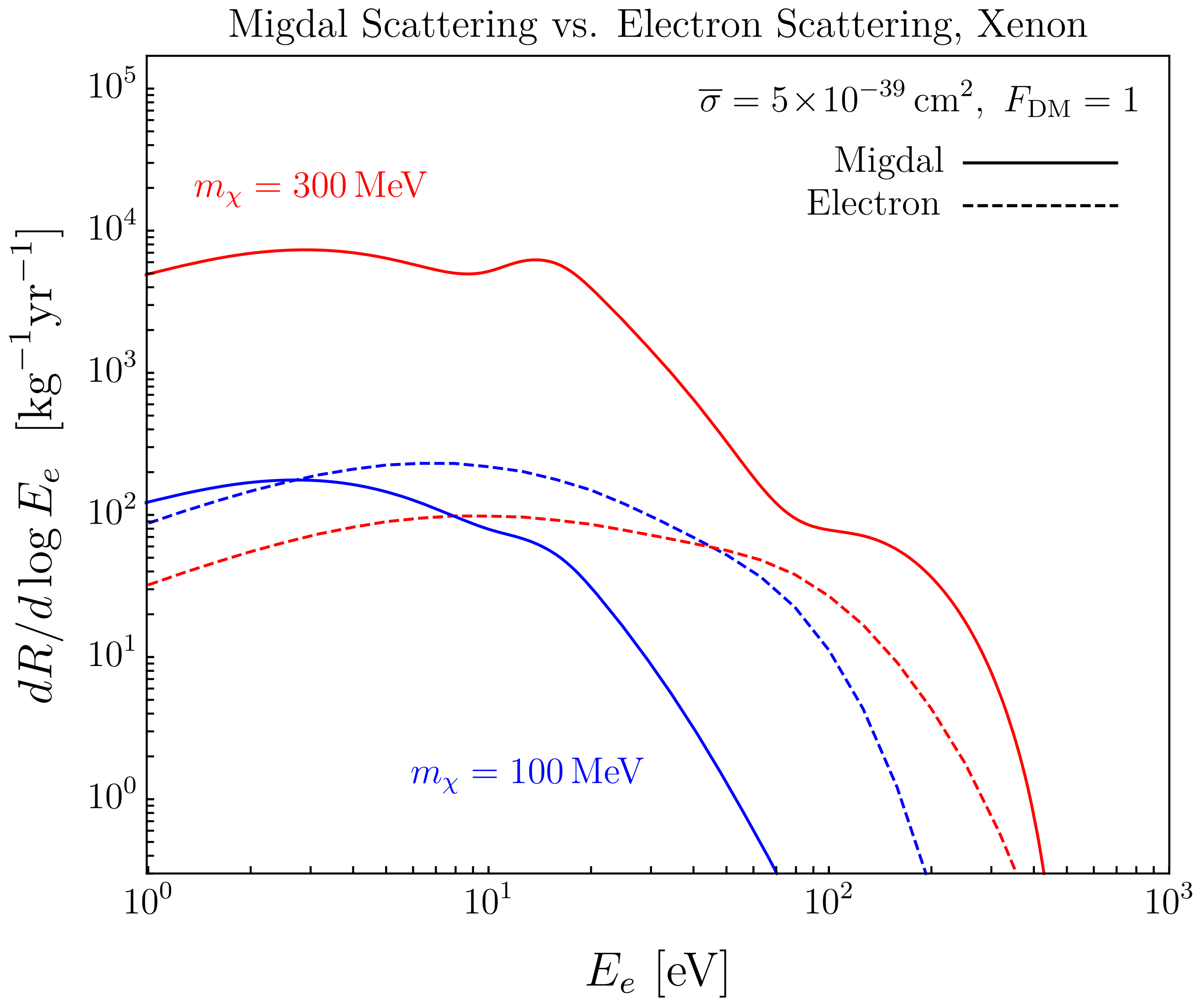


“electron recoil”

If you hit the nucleus:



“Migdal effect”



[Baxter, **YK**, Krnjaic 2019]

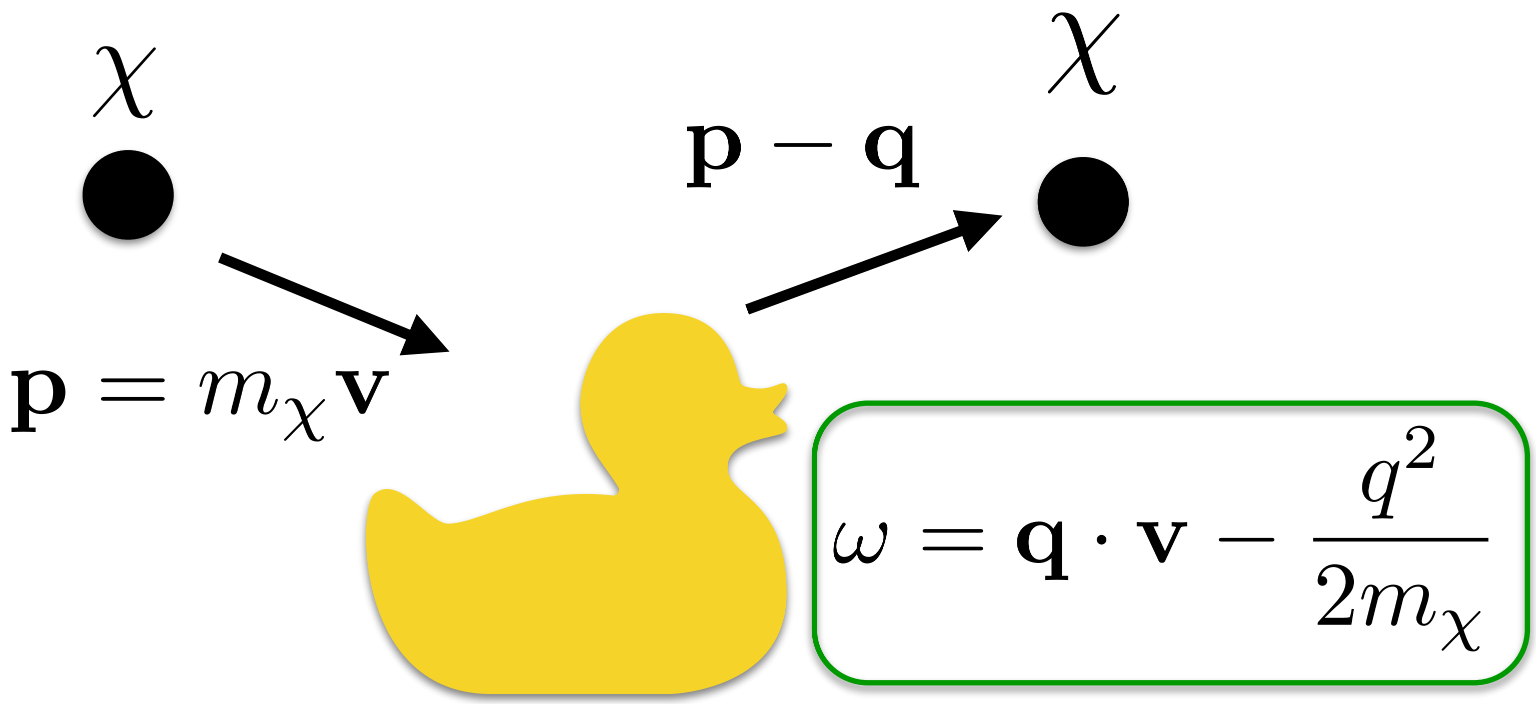
Same inelastic kinematics, vastly different dynamics!

A different perspective…

$$R \sim \int d^3\mathbf{v}\, f(\mathbf{v}) \int d^3\mathbf{q}\, F^2(\mathbf{q}) S(\mathbf{q}, \omega_{\mathbf{q}})$$

DM properties

Material properties (e.g. dielectric function)



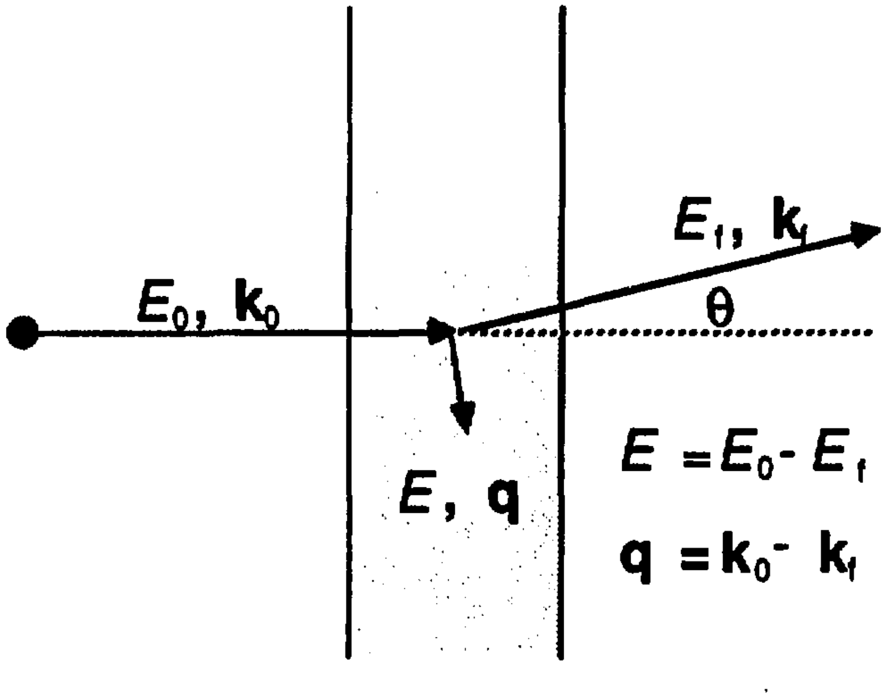
$$\omega = \mathbf{q} \cdot \mathbf{v} - \frac{q^2}{2m_\chi}$$

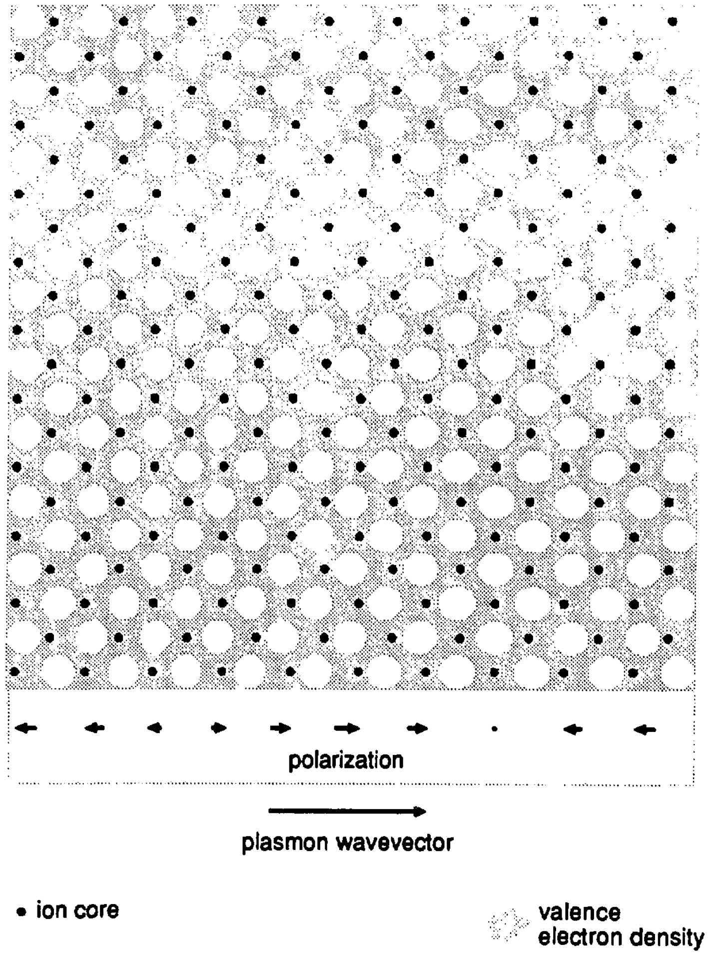
(insert your favorite detector here)

Something must respond at the appropriate $(\mathbf{q}, \omega)$:

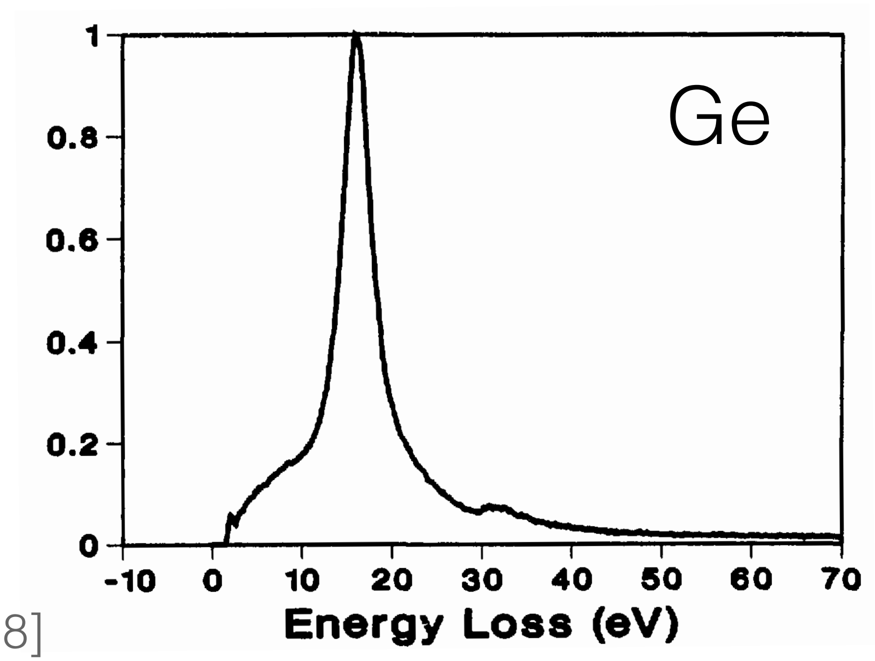
- electronic bands
- phonons
- magnons
- “free” nuclei (e.g. defects)
- atomic orbitals
- … and many more collective effects!

Example: EELS and plasmons



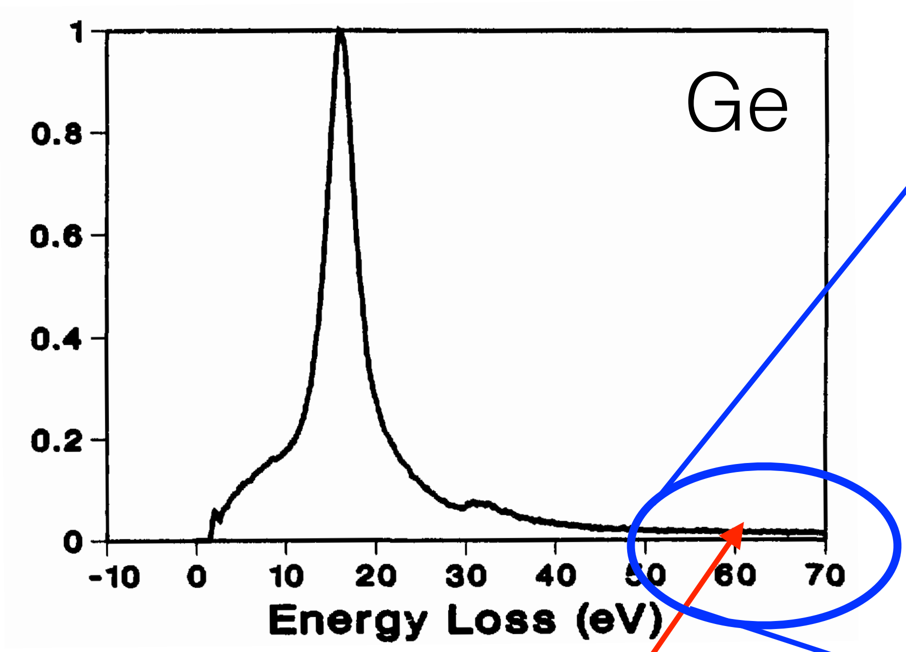


Semi-relativistic electron scattering **not** described by single-particle electron-electron scattering, but by a collective long-range charge wave (plasmon). Electron preferentially deposits ~15 eV of energy, **regardless of initial kinetic energy**

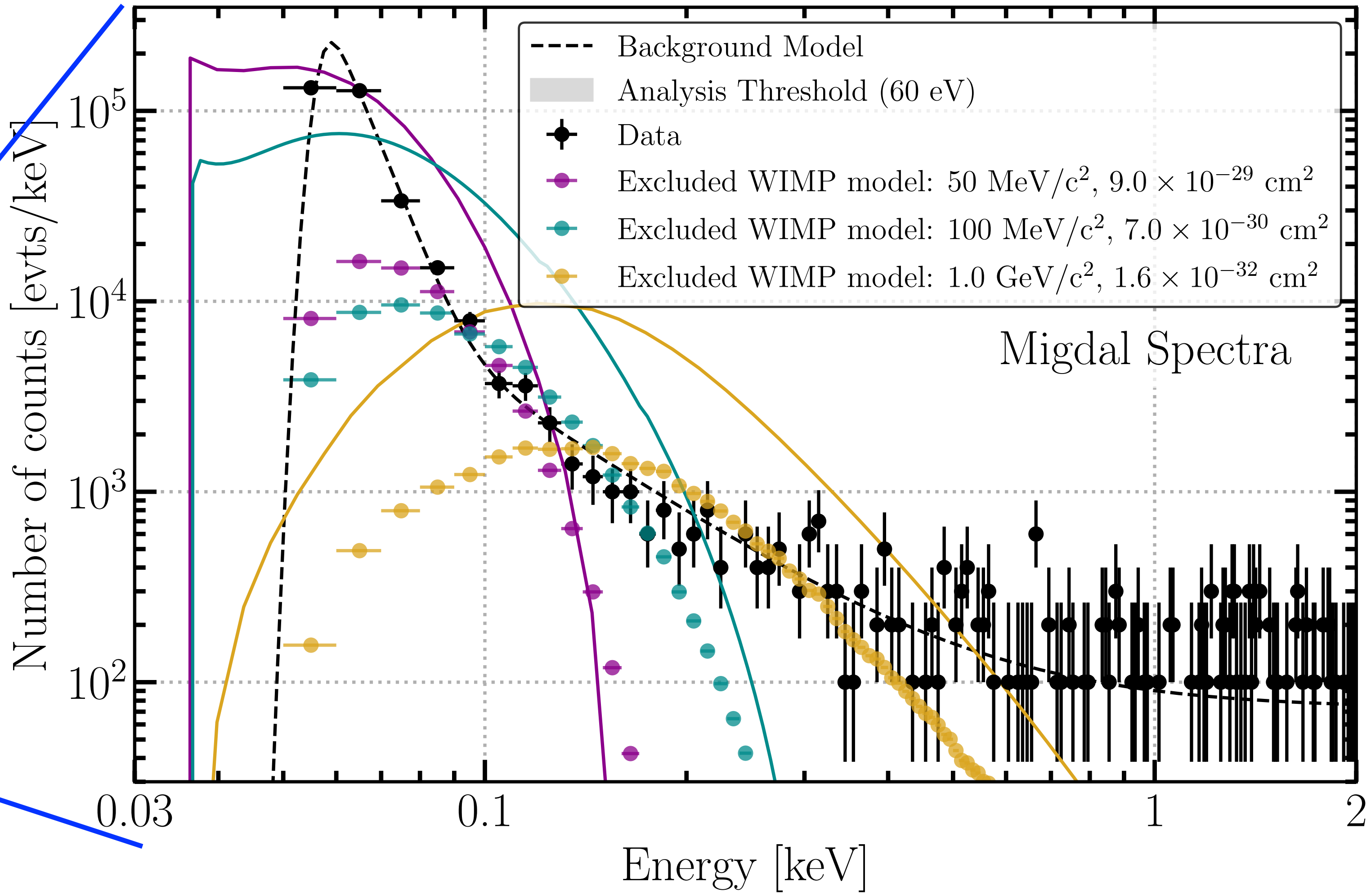


[M. Kundmann, Ph.D. thesis 1988]

A plasmon might look like this…

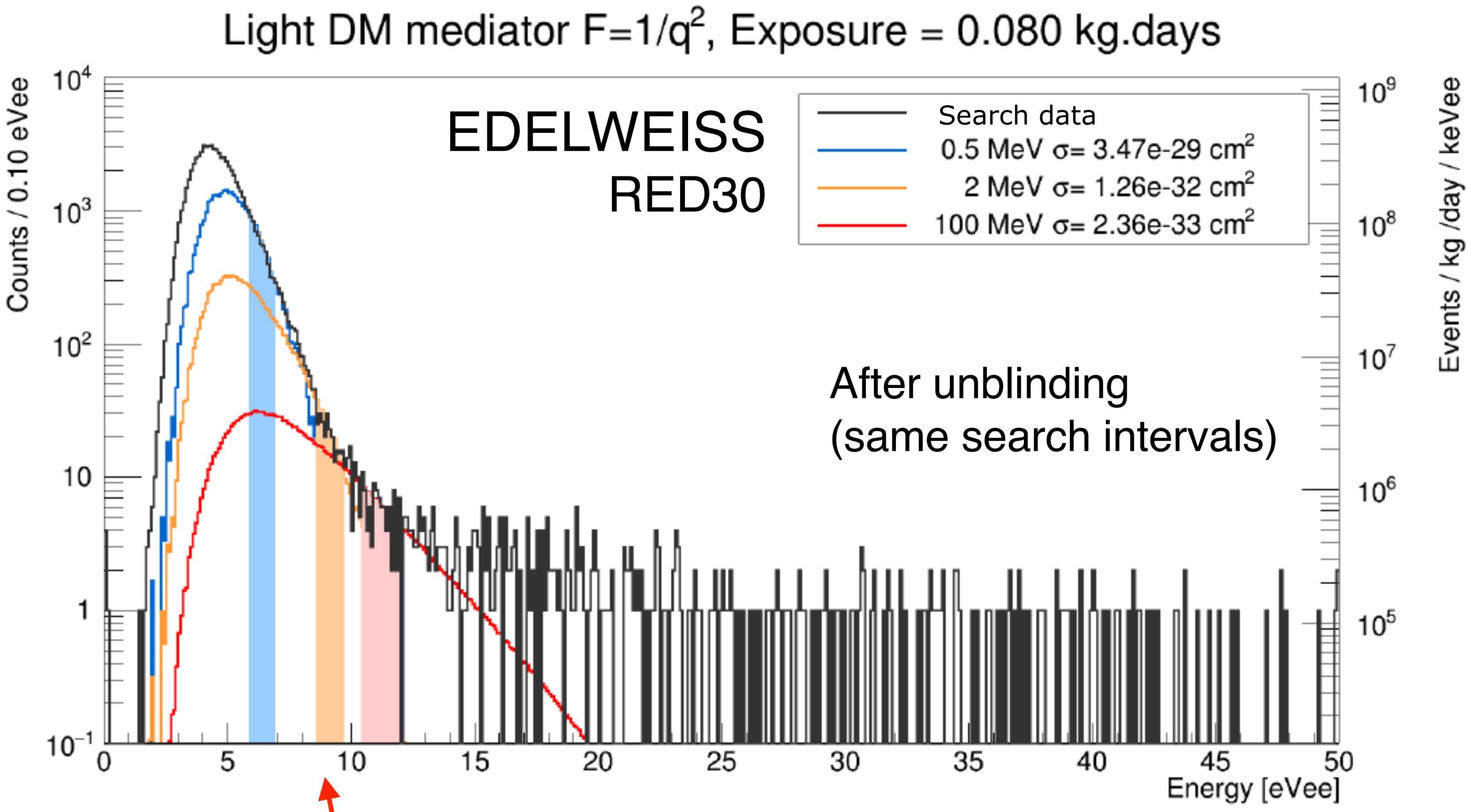


note the huge tail on a **linear** scale!



EDELWEISS surface (2019)
Germanium detector

Or it might look like this:



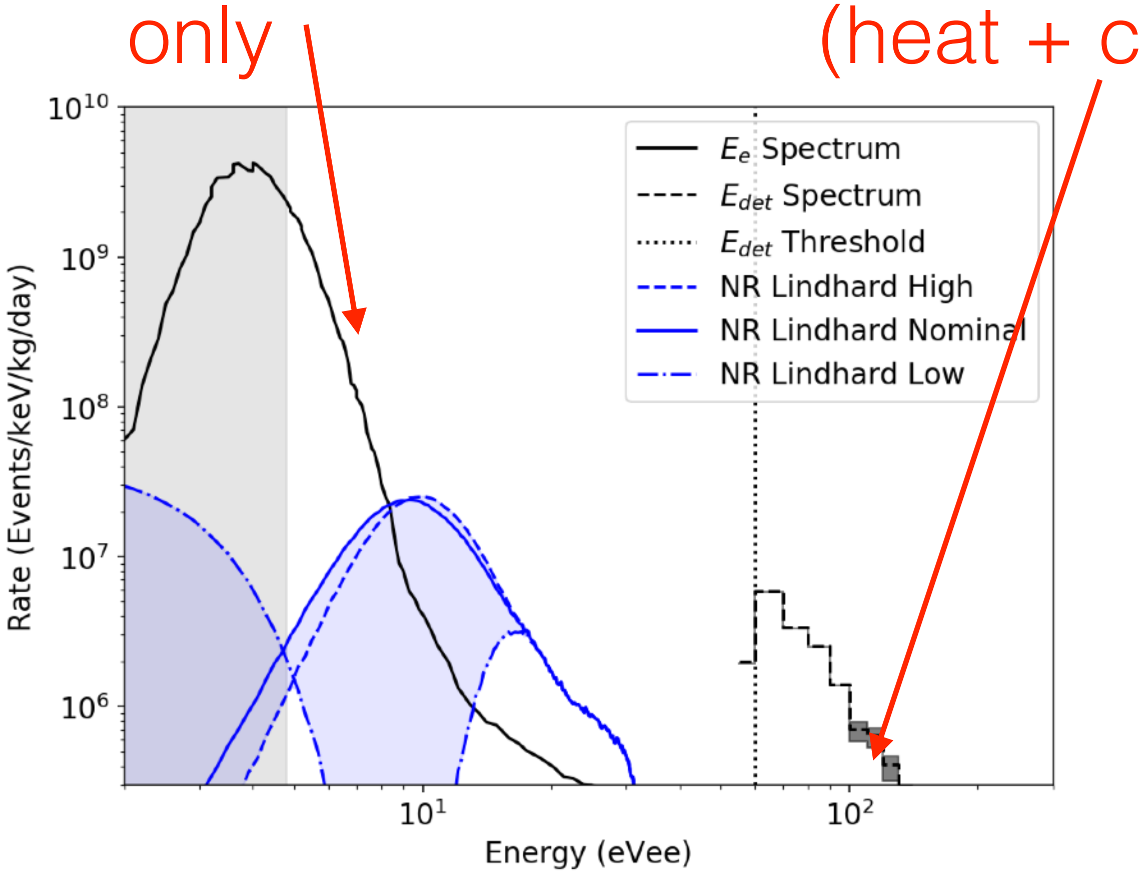
EDELWEISS underground (2020)

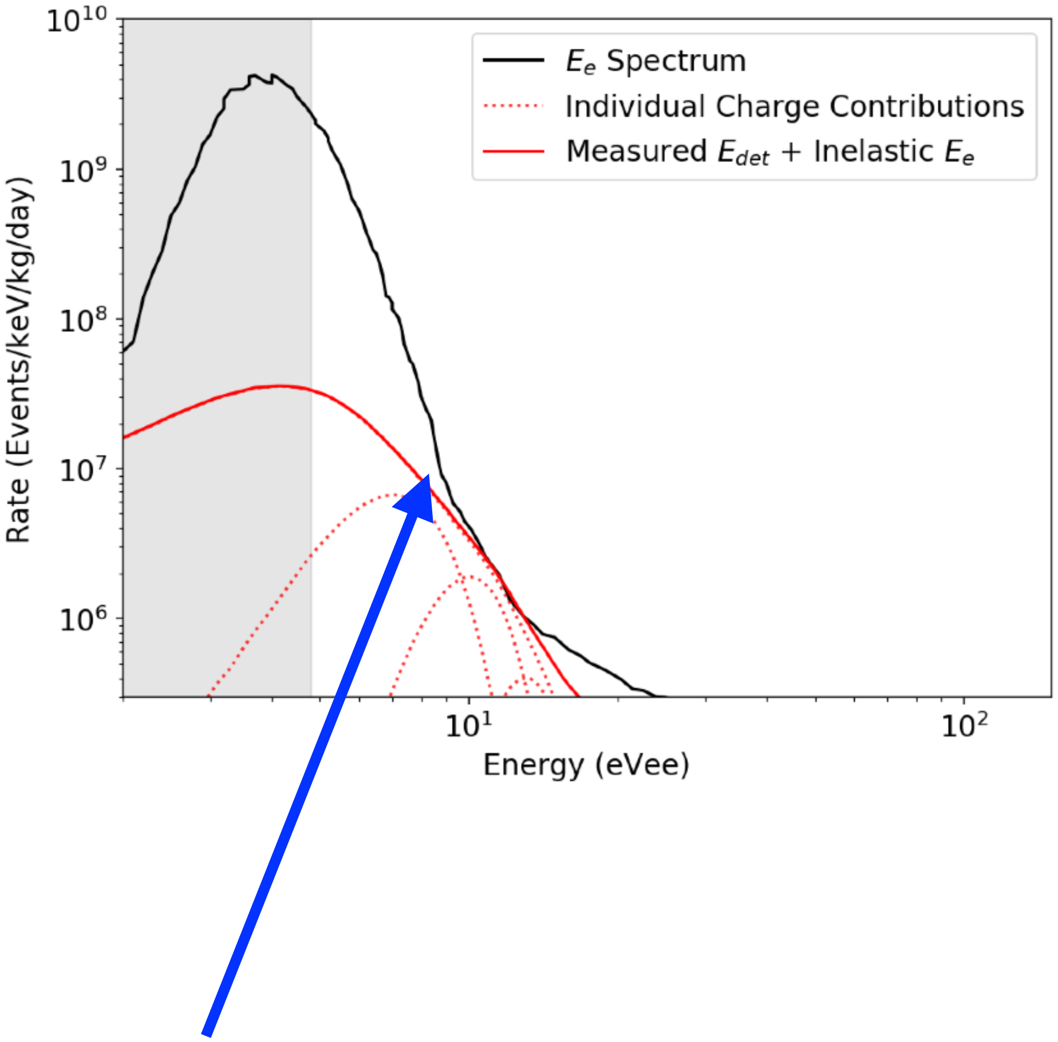
charge makes heat: this is really saying
“on average 1-2 e/h pairs per event”

Compare the two spectra:

electronic energy
only

all energy
(heat + charge)



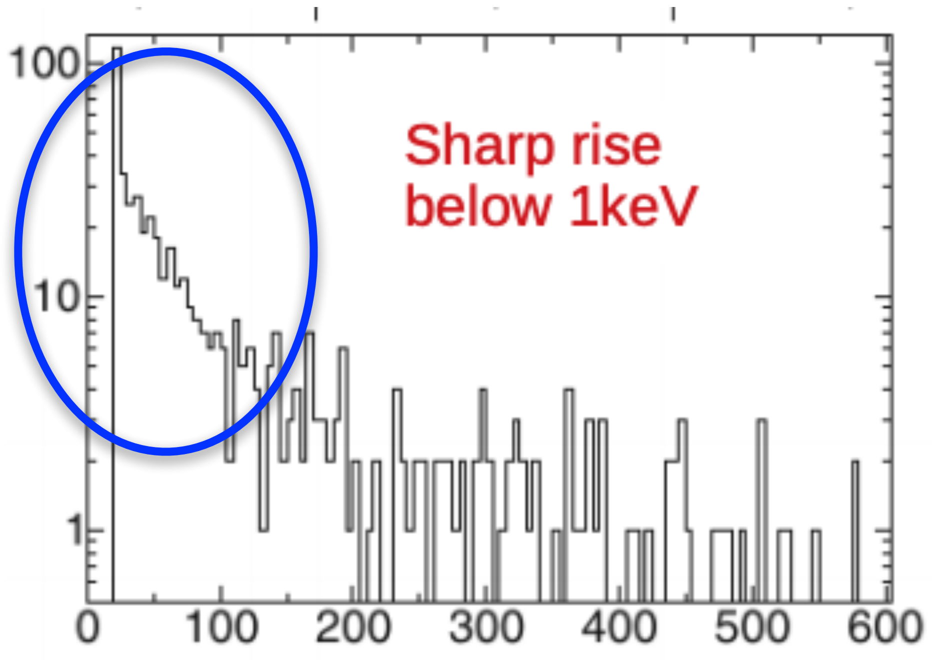


can't be nuclear recoil
or electron recoil…

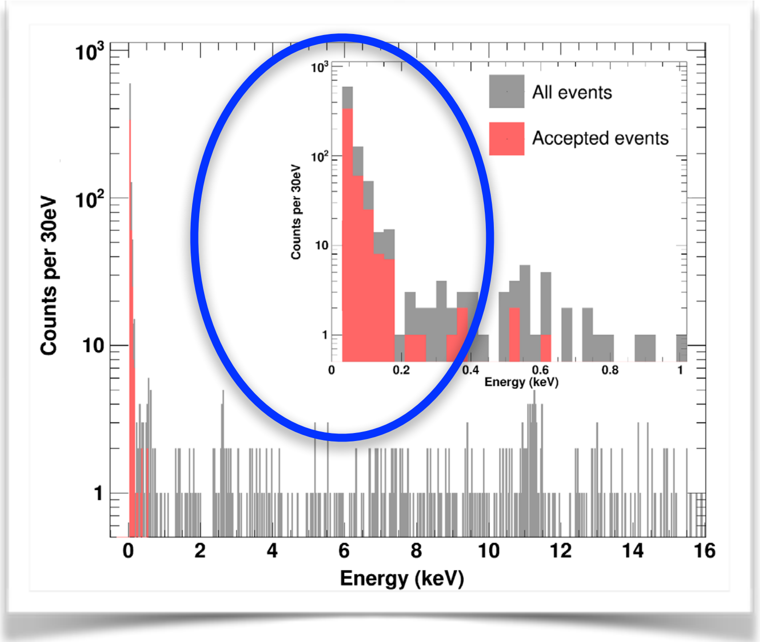
a model which works: every event makes ~2 e/h pairs plus phonons.
Consistent if large plasmon-phonon coupling

[Kurinsky, Baxter, **YK**, Krnjaic, to appear]

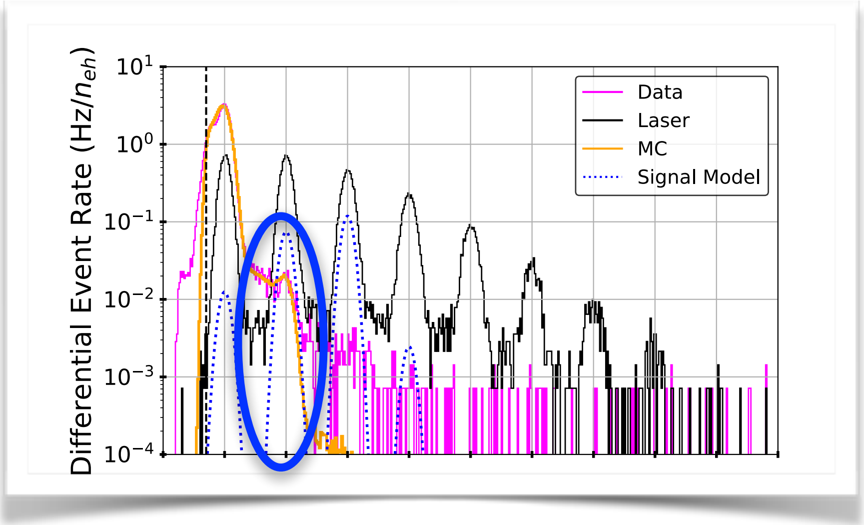
Once you start looking, you see it everywhere…



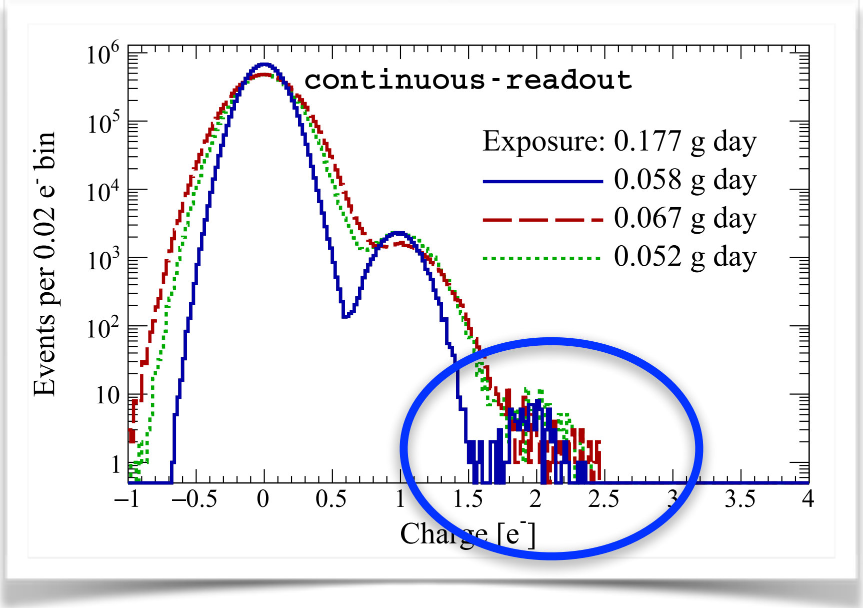
NUCLEUS surface Al_2O_3 (2017)



CRESST-III $CaWO_4$ (2019)



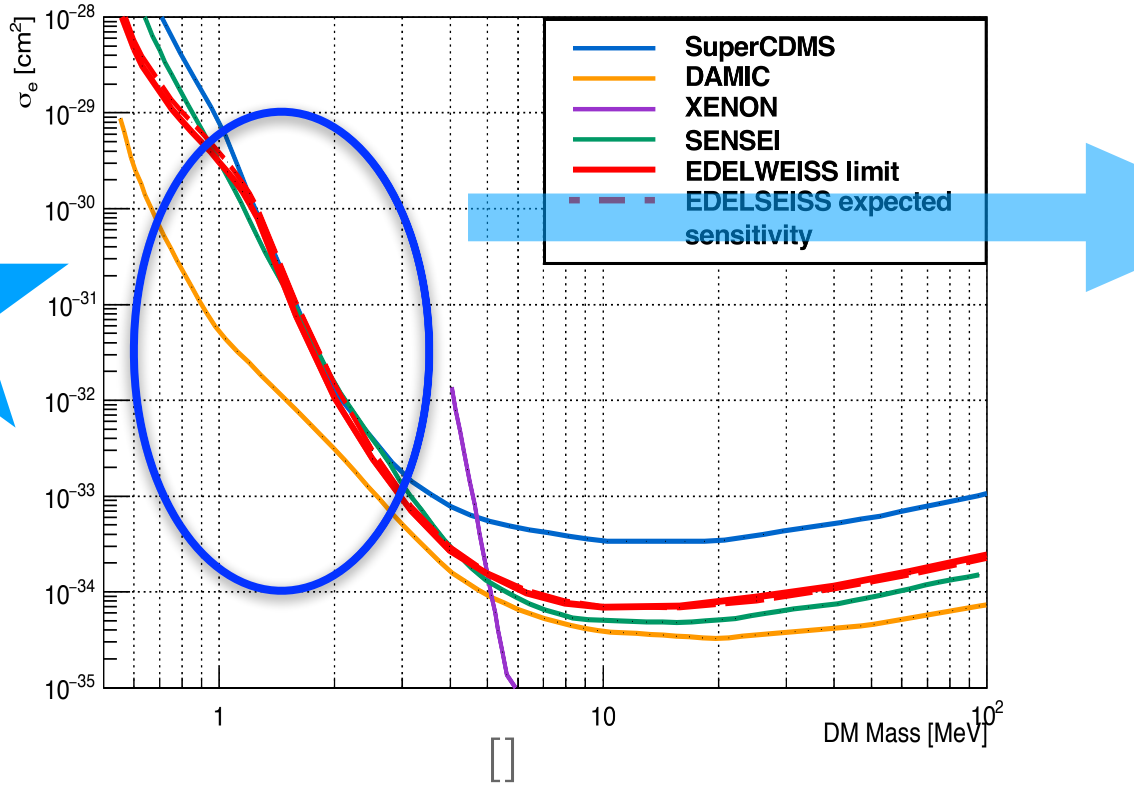
CDMS-HVeV Si (2018)

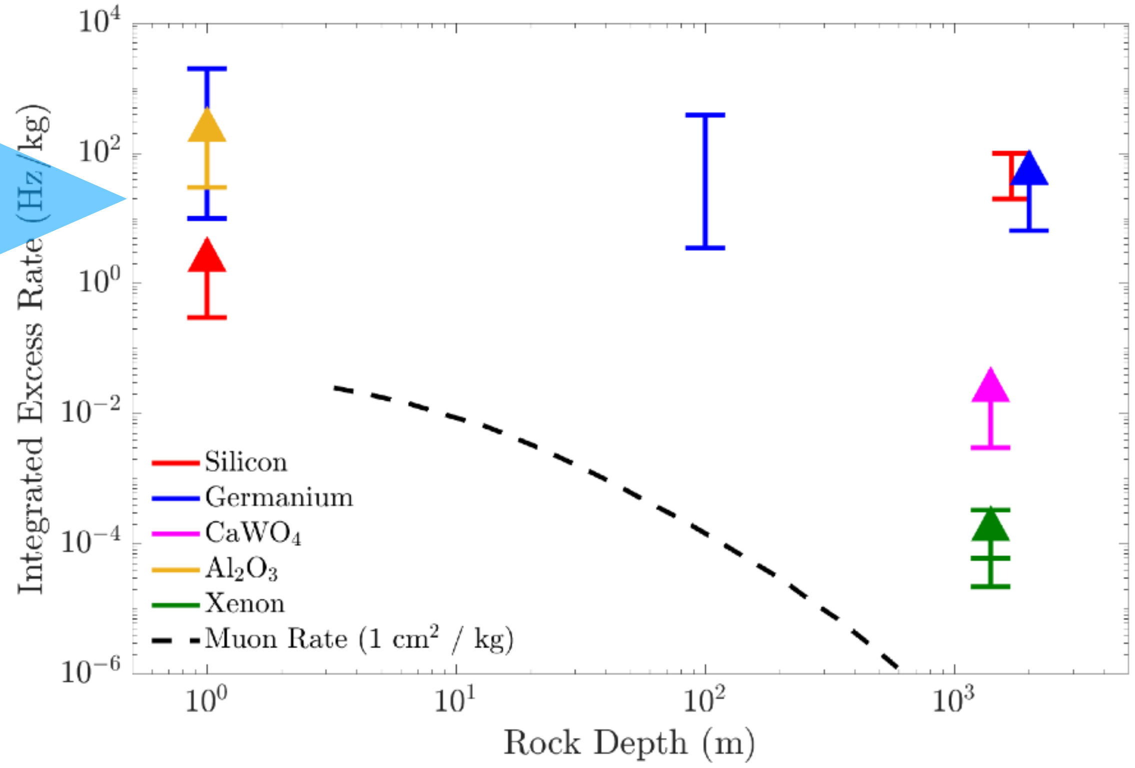


SENSEI underground Si (2019)

…and at the same rate!

Heavy Dark Sector mediator case (F=1)



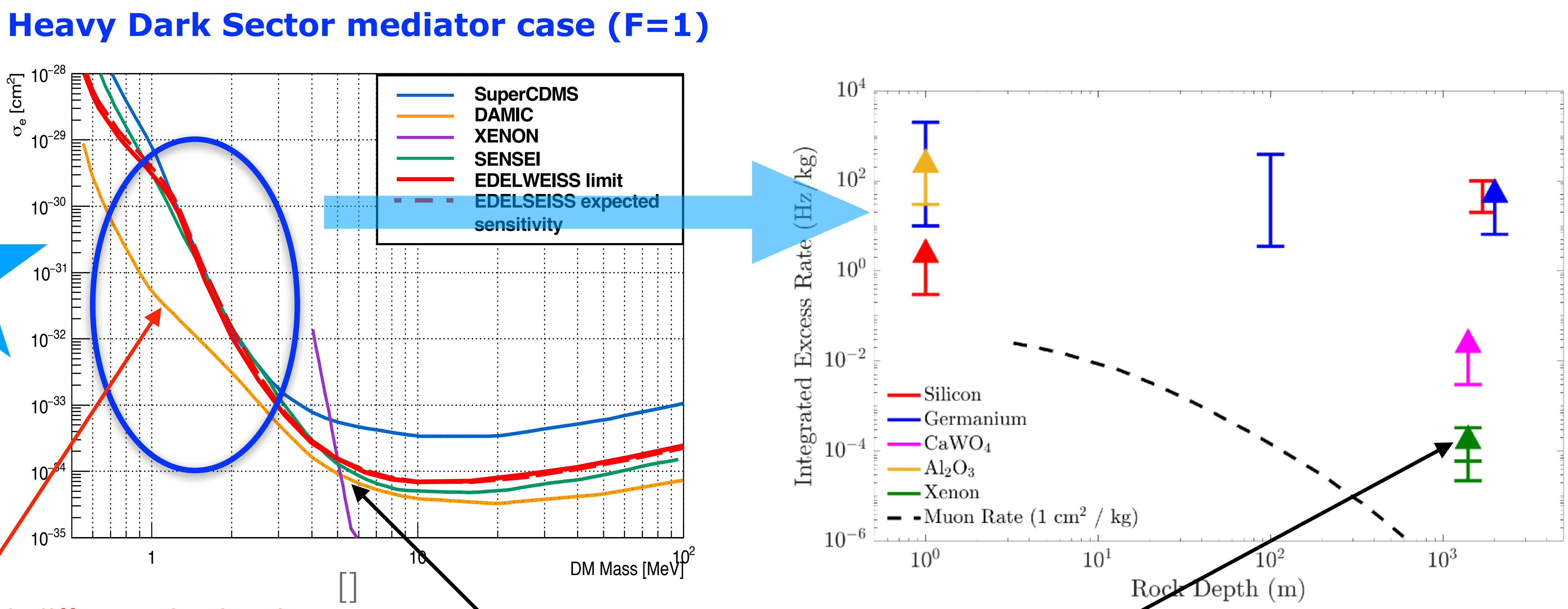


note: this limit plot assumes an electron recoil model.
This **DOES NOT** fit the spectrum!

But, obtaining the same cross section limits means the total 2-electron rate is the same everywhere

[EDELWEISS collab., talk at TMEX2020; Kurinsky, Baxter, **YK**, Krnjaic, to appear]

…and at the same rate!



DAMIC used different ionization model; under same model as CDMS and SENSEI, same limit

[Ramanathan and Kurinsky, to appear]

no plasmon in Xe, lower rate (bound does not apply)

note: this limit plot assumes an electron recoil model. This **DOES NOT** fit the spectrum!

But, obtaining the same cross section limits means the total 2-electron rate is the same everywhere

[EDELWEISS collab., talk at TMEX2020; Kurinsky, Baxter, **YK**, Krnjaic, to appear]

Something is making a plasmon at the same rate everywhere in every semiconductor detector

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Can it be dark matter?

Something is making a plasmon at the same rate everywhere in every semiconductor detector

Can it be dark matter?

To excite plasmon, need small $\mathbf{q}$ for fixed ω $\implies v \gtrsim 10^{-2}$

Faster than escape velocity! Either need fast DM, or indirect excitation

Two models:

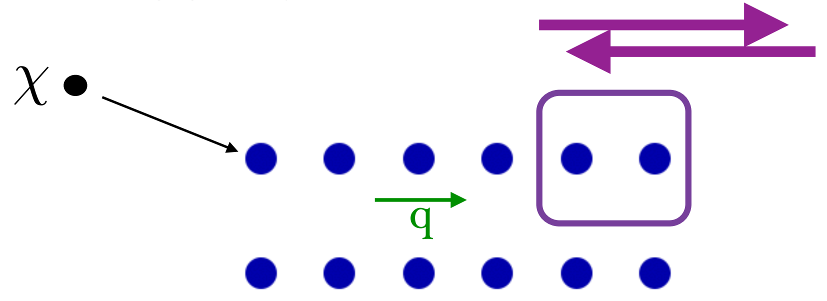
Heavy and slow

$m_{\mathrm{DM}} \sim 100\ \mathrm{MeV}$

$\mathrm{KE} \sim 100\ \mathrm{eV}$

plasmon

$(\omega \sim 15\ \mathrm{eV}, \mathbf{q} \sim 0)$

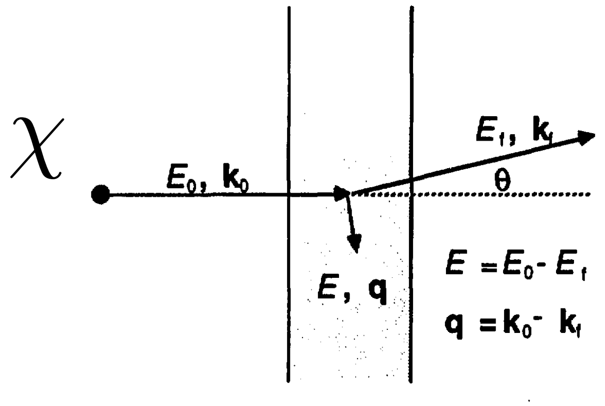


phonons

$(\mathbf{q} \sim 15\ \mathrm{keV})$

Fast and millicharged

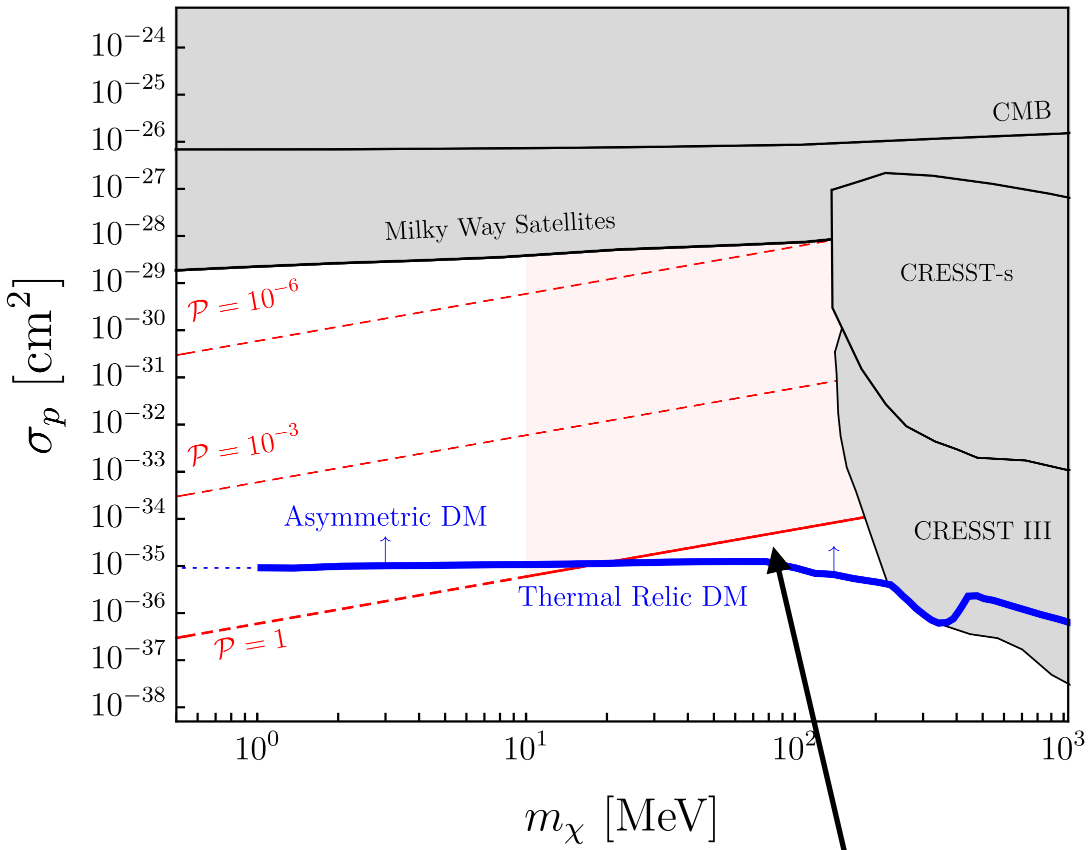
DM is like an electron,
with a long-range force.
Identical dynamics to EELS,
but **no multiple scattering**
in a thick detector



Parameter space

Heavy and slow

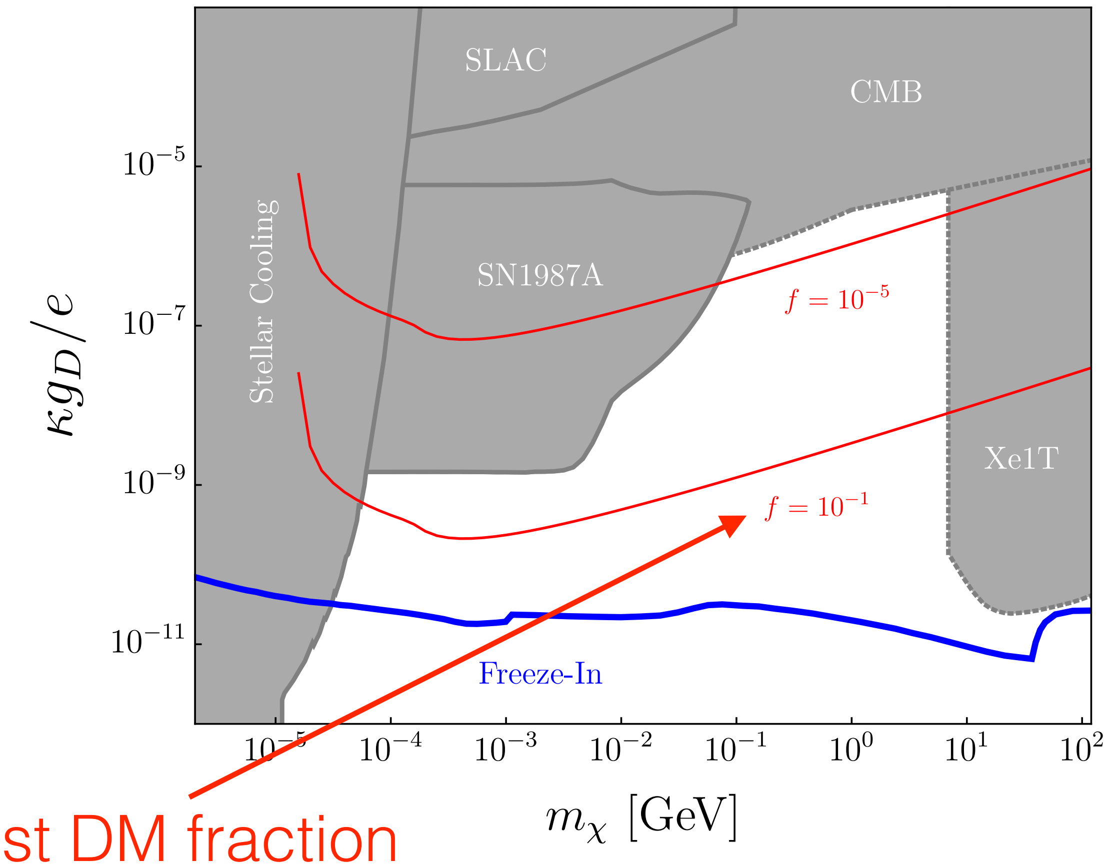
$$R \propto Z^2/A$$



Tantalizingly close to the thermal target…

Fast and millicharged

$$R \propto 1/\rho_T$$



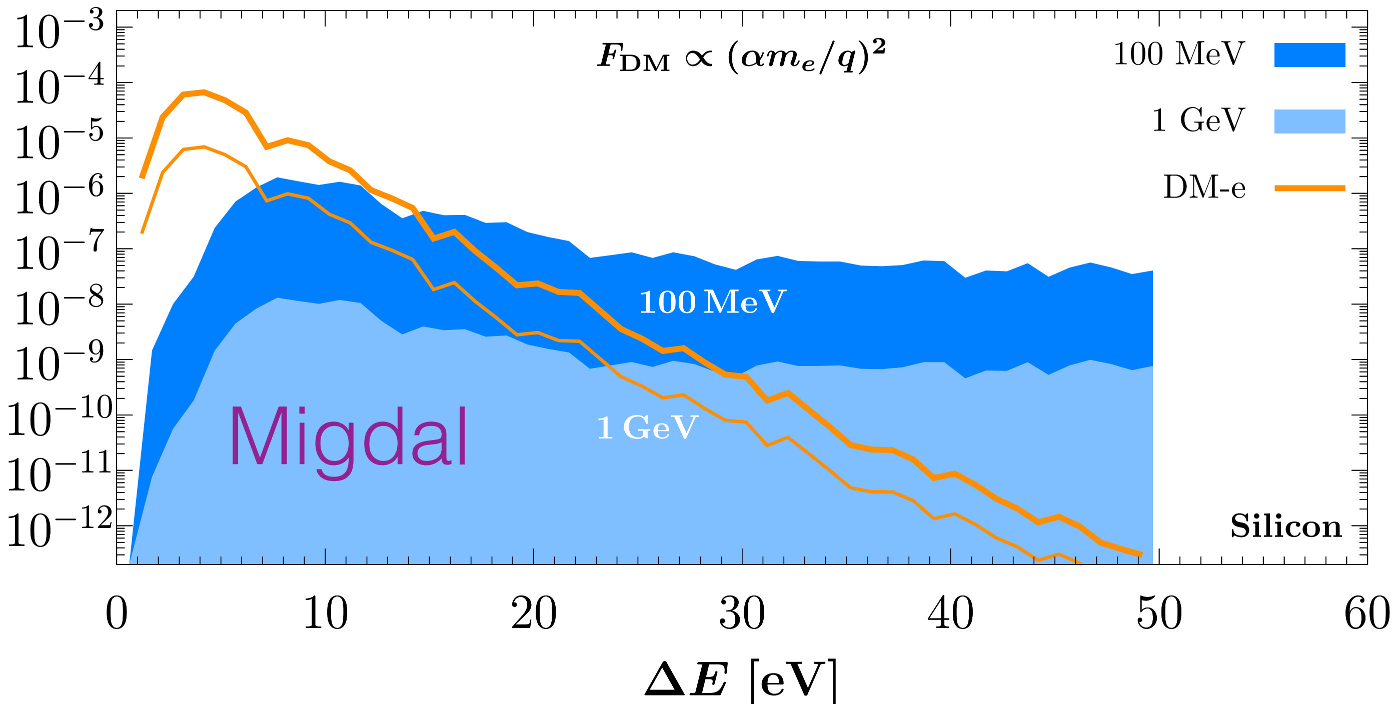
fast DM fraction

Suggests immediate discovery potential with 50 meV thresholds and mg-month exposures

[Kurinsky, Baxter, **YK**, Krnjaic]

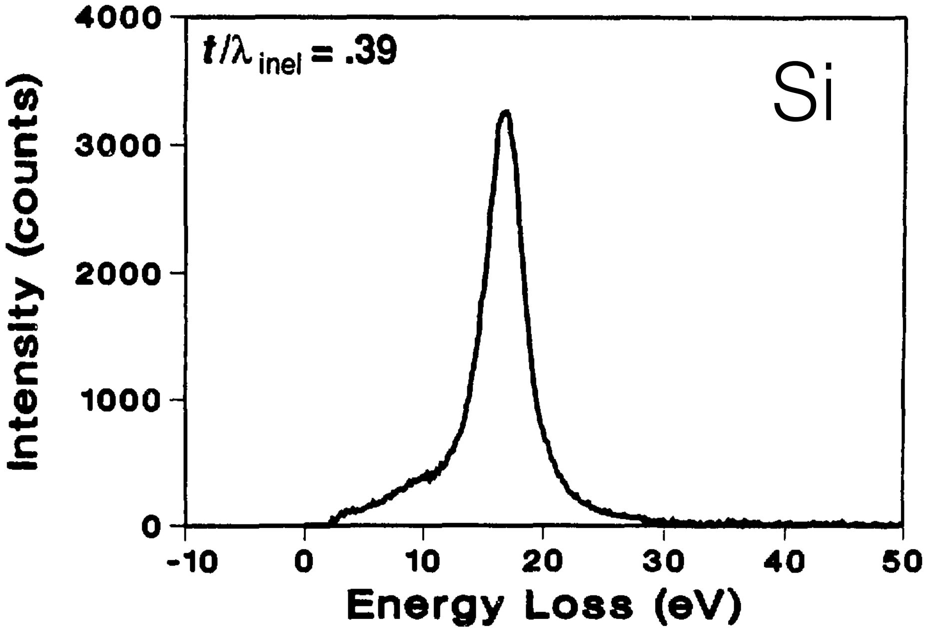
This is a completely new kind of signal

For direct plasmon excitation through a long-range force:



[Essig, Pradler, Sholapulkar, Yu, PRL 2020]

VS.



[M. Kundmann, Ph.D. thesis 1988]

Phonon detector: sharp peak at 15 eV with width 3 eV, long tail

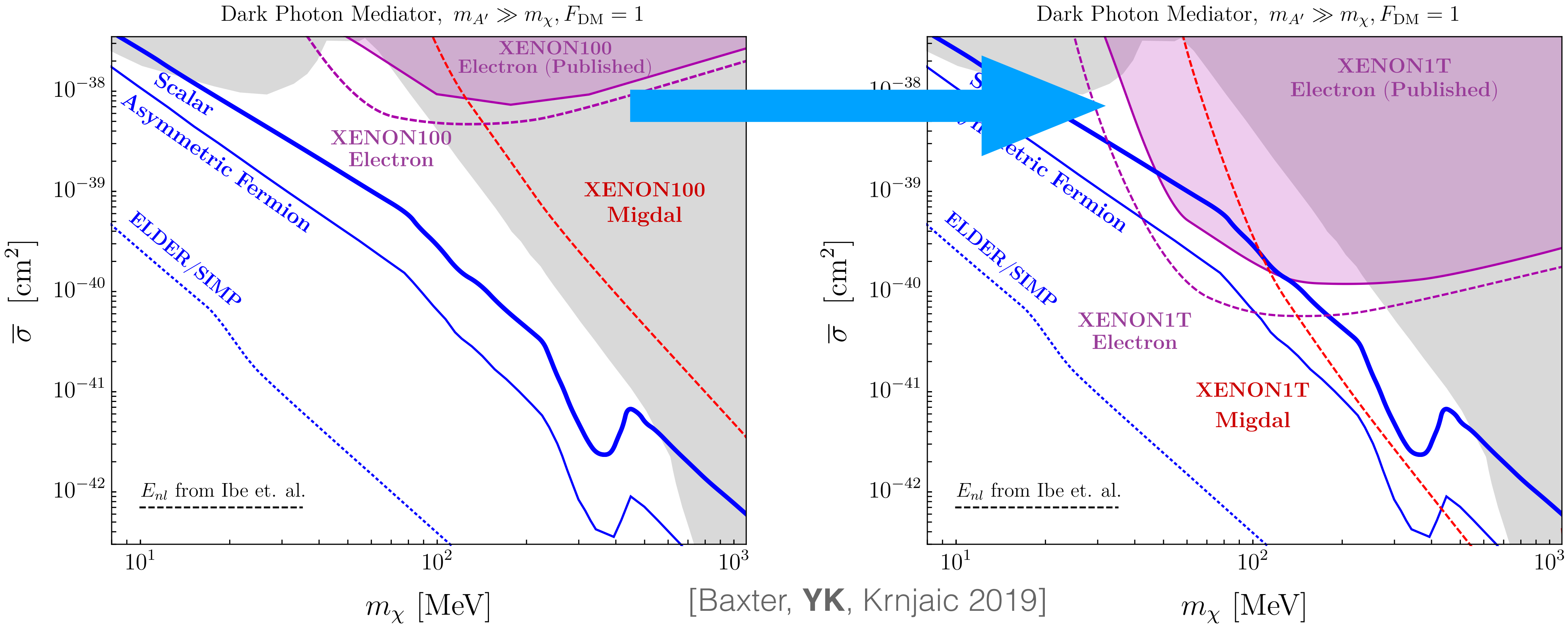
Charge detector: sharp peak in 2-electron bin, tail to 3 electrons

Looks nothing like electron recoil, nuclear recoil, or Migdal!

Quintessential many-body effect: only in semiconductors, not in Xe.

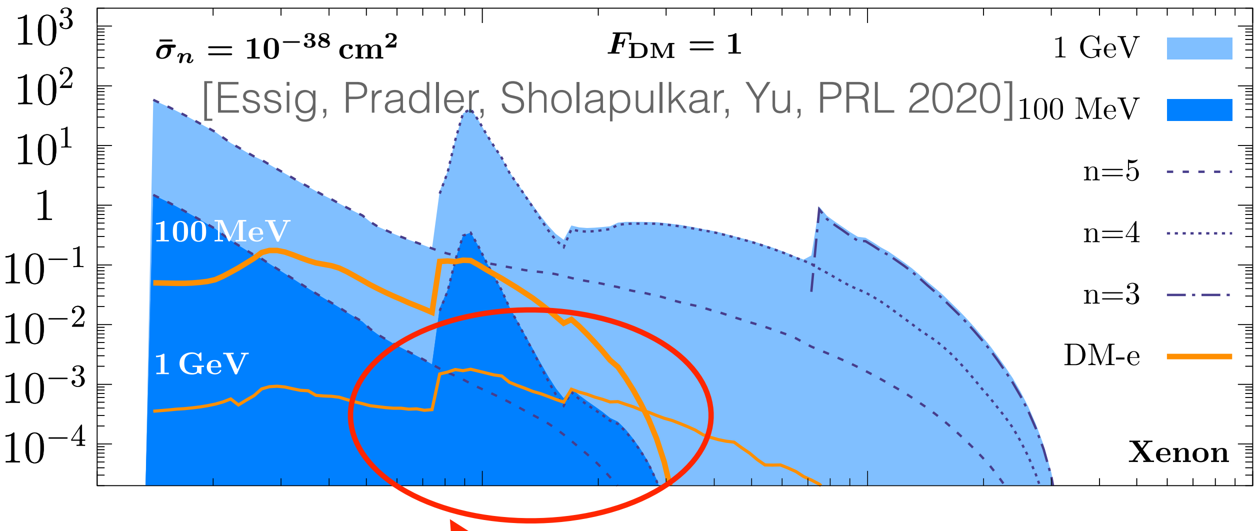
Spectrum determined by the material, NOT the DM!!

What about XENON?

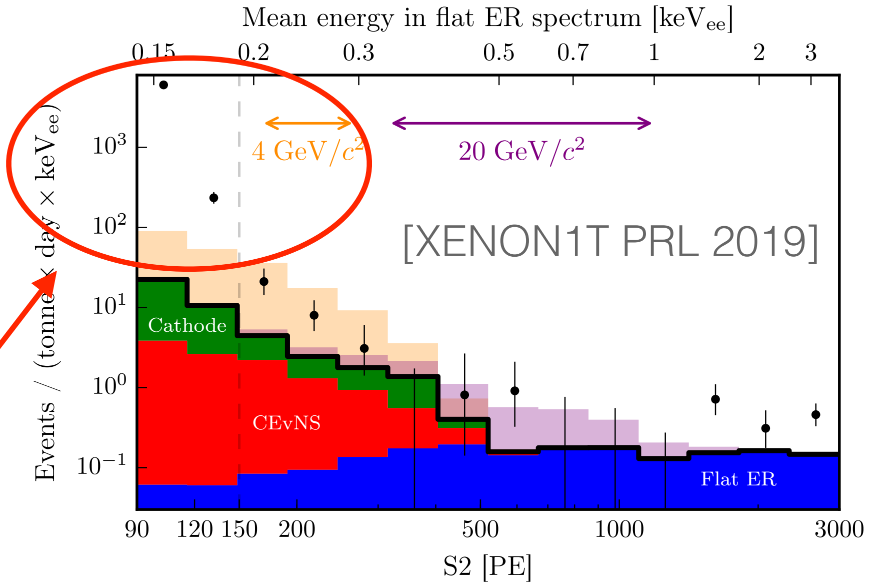


[Baxter, **YK**, Krnjaic 2019]

XENON1T seems to set a much stronger limit…



[Essig, Pradler, Sholapulkar, Yu, PRL 2020]



[XENON1T PRL 2019]

But sees an unexplained excess!

If signal is ER + Migdal, completely different signal shape

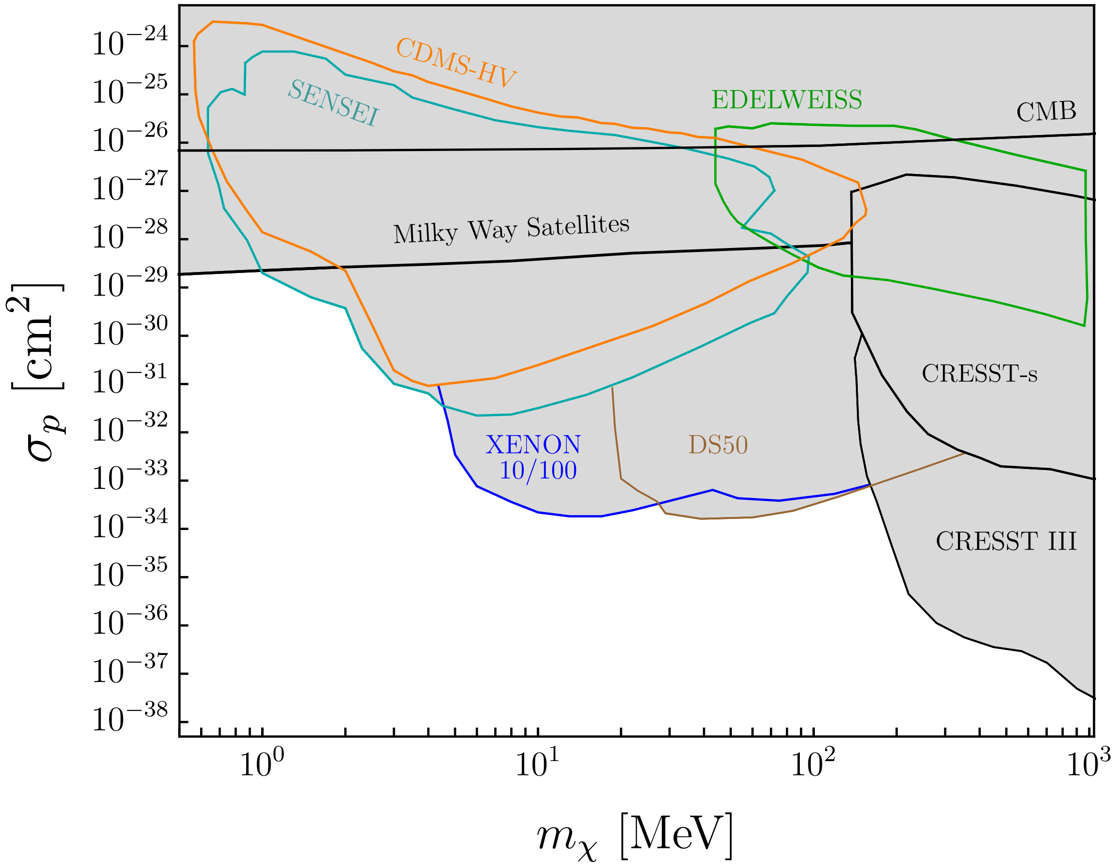
Conclusions

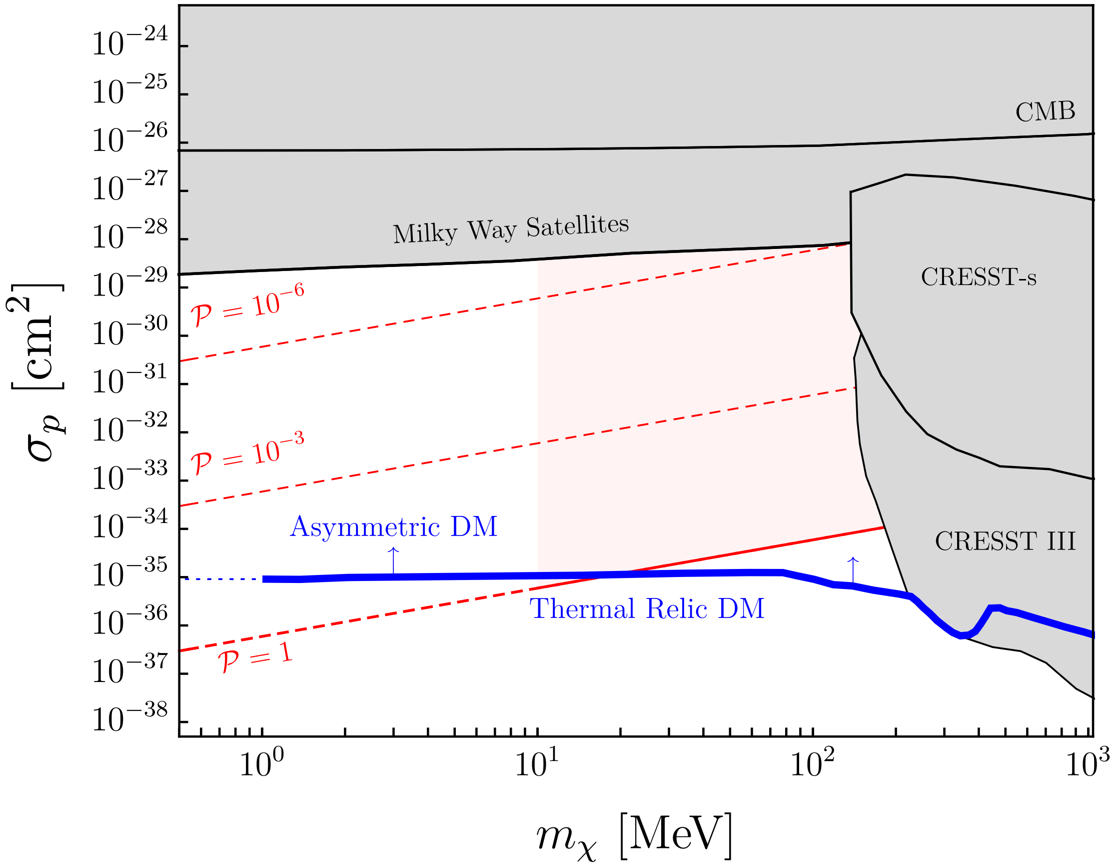
smaller = more speculative

- **There are lots of low-energy excesses**
- **The semiconductor rates are the same everywhere, regardless of overburden, exposure, or detector**
- Every semiconductor event is ~1-2 e/h pairs plus heat
- Every semiconductor event is a plasmon excitation
- Dark matter is exciting a plasmon in semiconductors and a combination of electron recoil and Migdal in noble liquids
- We've been seeing dark matter for the past 10 years!

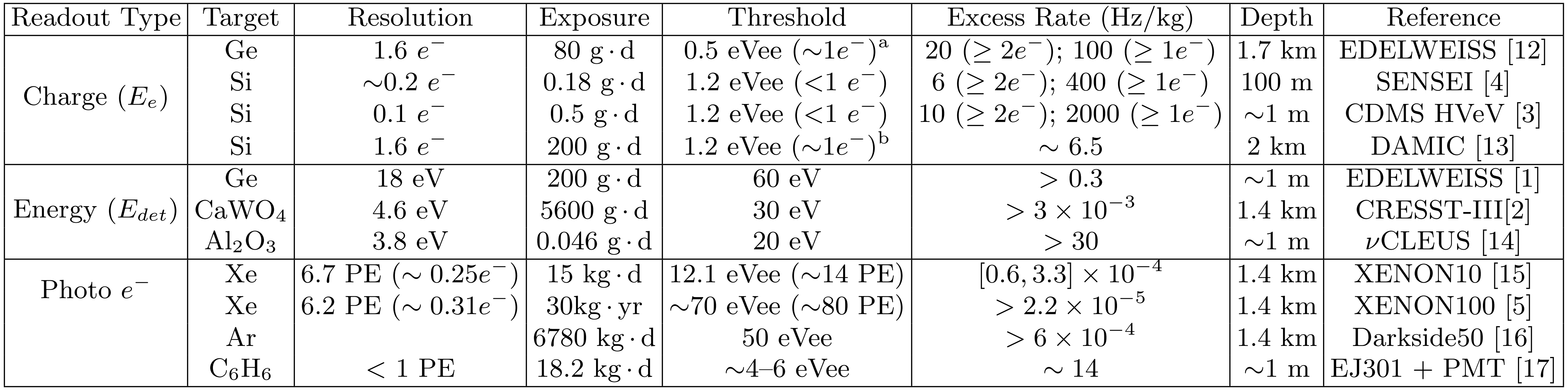
Backup slides

Naive nuclear recoil limits





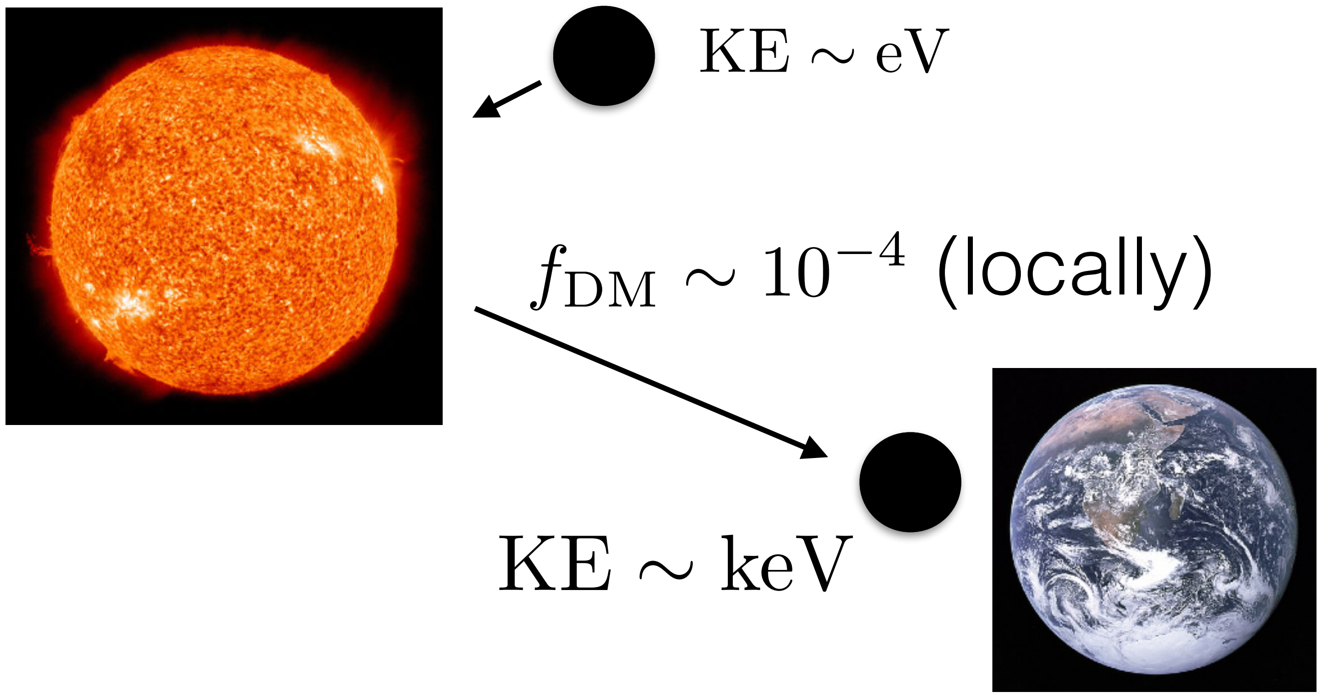
All the excesses



Readout Type	Target	Resolution	Exposure	Threshold	Excess Rate (Hz/kg)	Depth	Reference
Charge (E_e)	Ge	1.6 e^-	80 $\mathrm{g \cdot d}$	0.5 eVee ($\sim 1e^-$)[a]	20 ($\geq 2e^-$); 100 ($\geq 1e^-$)	1.7 km	EDELWEISS [12]
	Si	$\sim$0.2 e^-	0.18 $\mathrm{g \cdot d}$	1.2 eVee ($<$1 e^-)	6 ($\geq 2e^-$); 400 ($\geq 1e^-$)	100 m	SENSEI [4]
	Si	0.1 e^-	0.5 $\mathrm{g \cdot d}$	1.2 eVee ($<$1 e^-)	10 ($\geq 2e^-$); 2000 ($\geq 1e^-$)	$\sim$1 m	CDMS HVeV [3]
	Si	1.6 e^-	200 $\mathrm{g \cdot d}$	1.2 eVee ($\sim 1e^-$)[b]	~ 6.5	2 km	DAMIC [13]
Energy (E_{det})	Ge	18 eV	200 $\mathrm{g \cdot d}$	60 eV	> 0.3	$\sim$1 m	EDELWEISS [1]
	$CaWO_4$	4.6 eV	5600 $\mathrm{g \cdot d}$	30 eV	$> 3 \times 10^{-3}$	1.4 km	CRESST-III[2]
	Al_2O_3	3.8 eV	0.046 $\mathrm{g \cdot d}$	20 eV	> 30	$\sim$1 m	νCLEUS [14]
Photo e^-	Xe	6.7 PE ($\sim 0.25e^-$)	15 $\mathrm{kg \cdot d}$	12.1 eVee ($\sim$14 PE)	$[0.6, 3.3] \times 10^{-4}$	1.4 km	XENON10 [15]
	Xe	6.2 PE ($\sim 0.31e^-$)	30$\mathrm{kg \cdot yr}$	$\sim$70 eVee ($\sim$80 PE)	$> 2.2 \times 10^{-5}$	1.4 km	XENON100 [5]
	Ar		6780 $\mathrm{kg \cdot d}$	50 eVee	$> 6 \times 10^{-4}$	1.4 km	Darkside50 [16]
	C_6H_6	$<$ 1 PE	18.2 $\mathrm{kg \cdot d}$	$\sim$4–6 eVee	~ 14	$\sim$1 m	EJ301 + PMT [17]

Models for millicharge acceleration

Solar reflection



$m_{\mathrm{DM}} \sim \mathrm{keV}$

$\mathrm{KE} \sim \mathrm{eV}$

$f_{\mathrm{DM}} \sim 10^{-4}$ (locally)

$\mathrm{KE} \sim \mathrm{keV}$

Cosmic ray upscattering

Supernova acceleration