Nuclear and atomic physics topics in Direct Dark Matter Detection

- Quenching factors (light/ionization yields)
- Nuclear form factors/Channeling effects
- Detection channels (Axion detection)
- Outlooks & Prospects

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(Axion Materials Provided by Dr. ShuKui Liu)

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Direct detection: Start off the beginning…

Detected rate

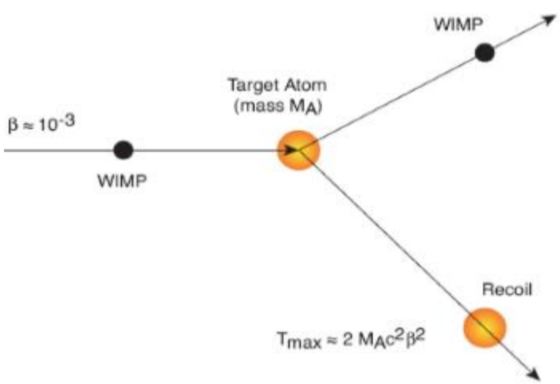
Nuclear form factor

Astrophysics model (ρ_0, v_0, v_{esc})

$$\frac{dN^{SI}}{dE} = \frac{2M_{det}t}{\pi}\frac{\rho_0}{M_\chi}F_A^2(q)\left(\lambda_p Z + \lambda_n(A-Z)\right)^2 I(E)$$

Exposure

Cross section



Ionization

Scintillation

Bolometer

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Detected rate

Nuclear form factor

Astrophysics models (ρ_0, v_0, v_{esc})

$$\frac{dN^{SI}}{dE} = \frac{2M_{det}t}{\pi}\frac{\rho_0}{M_\chi}F_A^2(q)\left(\lambda_p Z + \lambda_n(A - Z)\right)^2 I(E)$$

Quenching Factor

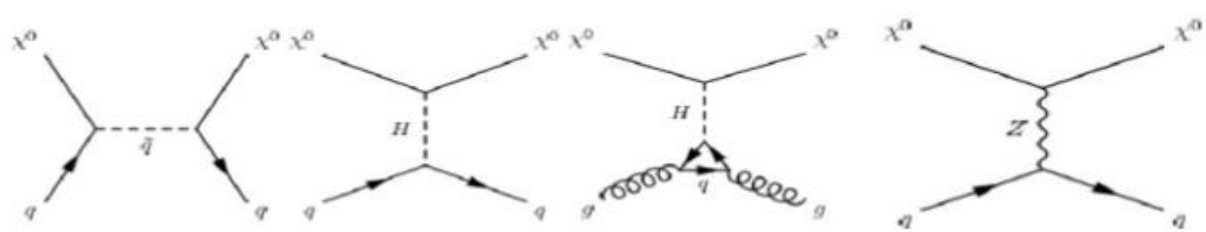
Exposure

Cross section (Particle Physics + quark content in nucleon)

Detector response models: Quenching factor; Channeling effects ; QED at low energy of keV

Atomic/Nuclear Physics

Detection channels
χe- scattering ;
ALP DM searches ;
hidden photons ;
Atomic ionization...



Quenching Factors

Nuclear recoil energy ≠ Ionization detectors : Ge, Xe, Ar…

Scintillation detectors: Xe, Ar, $CaWO_4$, CsI, NaI…

- **Experimental Fact** : Amount of charge/light yields by nuclear recoils is lower than that produced by electrons of the same energy.
- **Models** : Birks approach (1951) in description of light yields ; Lindhard theory (1965) . Both in materials depend on energy E, as well as the stopping power dE/dr.

Models on the Quenching Factors

- Lindhard theory for ionization detectors represents :

$$f_n = \frac{kg(\varepsilon)}{1 + kg(\varepsilon)}$$

where

$$\varepsilon = 11.5\, E_R(\mathrm{keV})\, Z^{-7/3}$$
$$g(\varepsilon) = 3\,\varepsilon^{0.15} + 0.7\,\varepsilon^{0.6} + \varepsilon$$

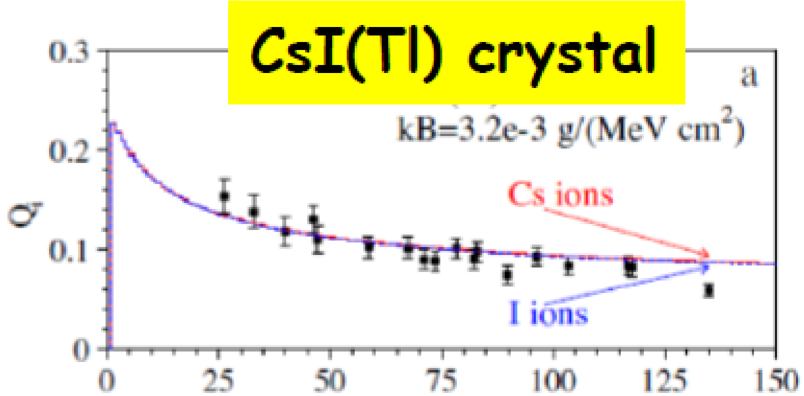
- Birks theory

$$\frac{dL}{dr} = S\frac{dE}{dr}$$, where S is the absolute scintillation factor

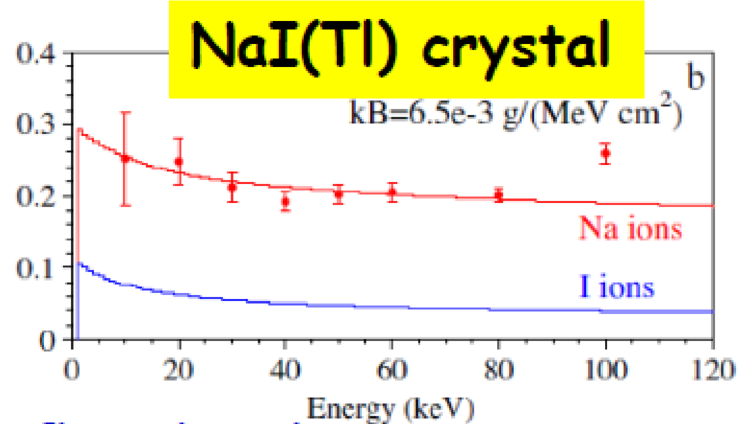
$$\frac{dL}{dr} = \frac{S\frac{dE}{dr}}{1 + kB\frac{dE}{dr}} \; ; \quad L(E) = \int_0^E dL = \int_0^E \frac{S\,dE}{1 + kB\frac{dE}{dr}}$$

- Choices on Stopping Power dE/dr : ESTAR code; SRIM/TRIM codes [J. F. Ziegler and J. P. Biersack 1985, 2009]; D. Mei et al., [AP 2008, 2010]

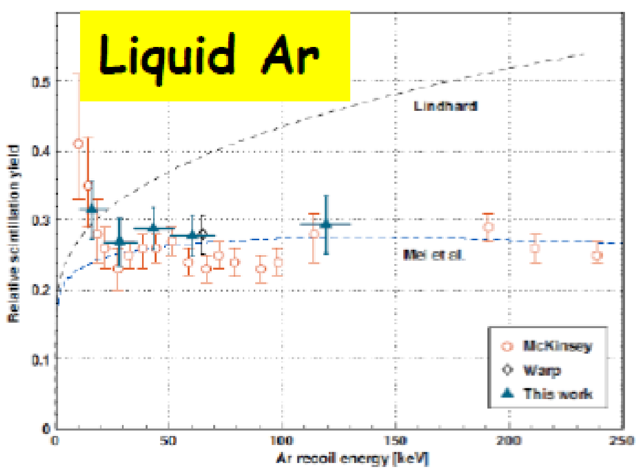
Comparing the experimental and calculated QF



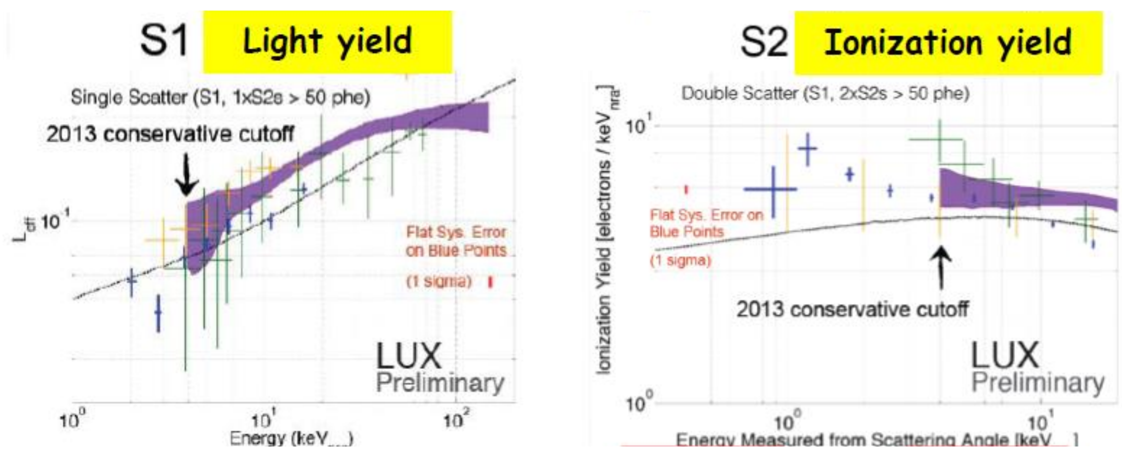
S. Pecourt et al., AP 11 (1999) 457



H. Chagani et al., JINST 3 (2008) P06003



C. Regenfus et al. JPCS 375 (2012) 012019



NEXT model for LUX (181V/cm)

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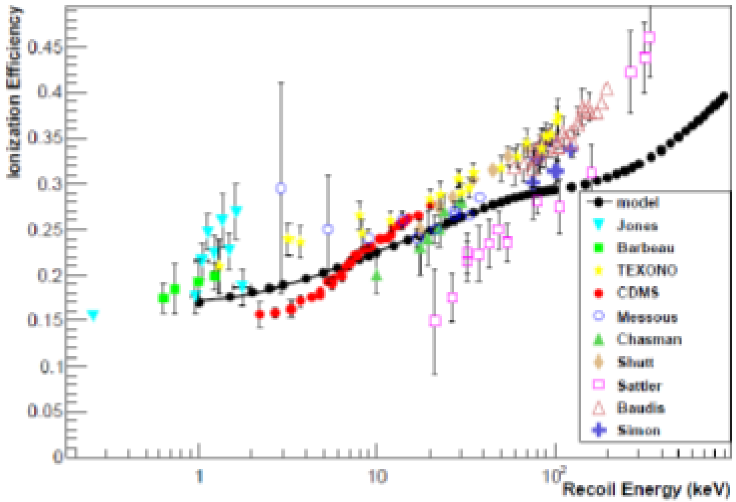
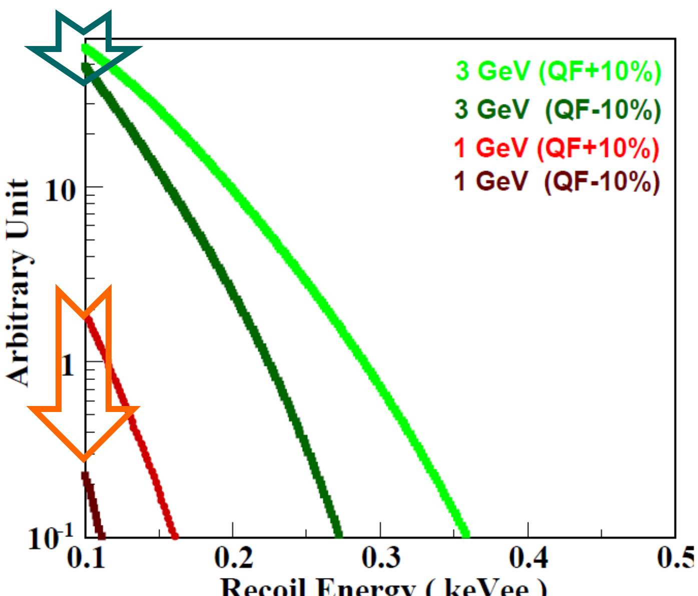
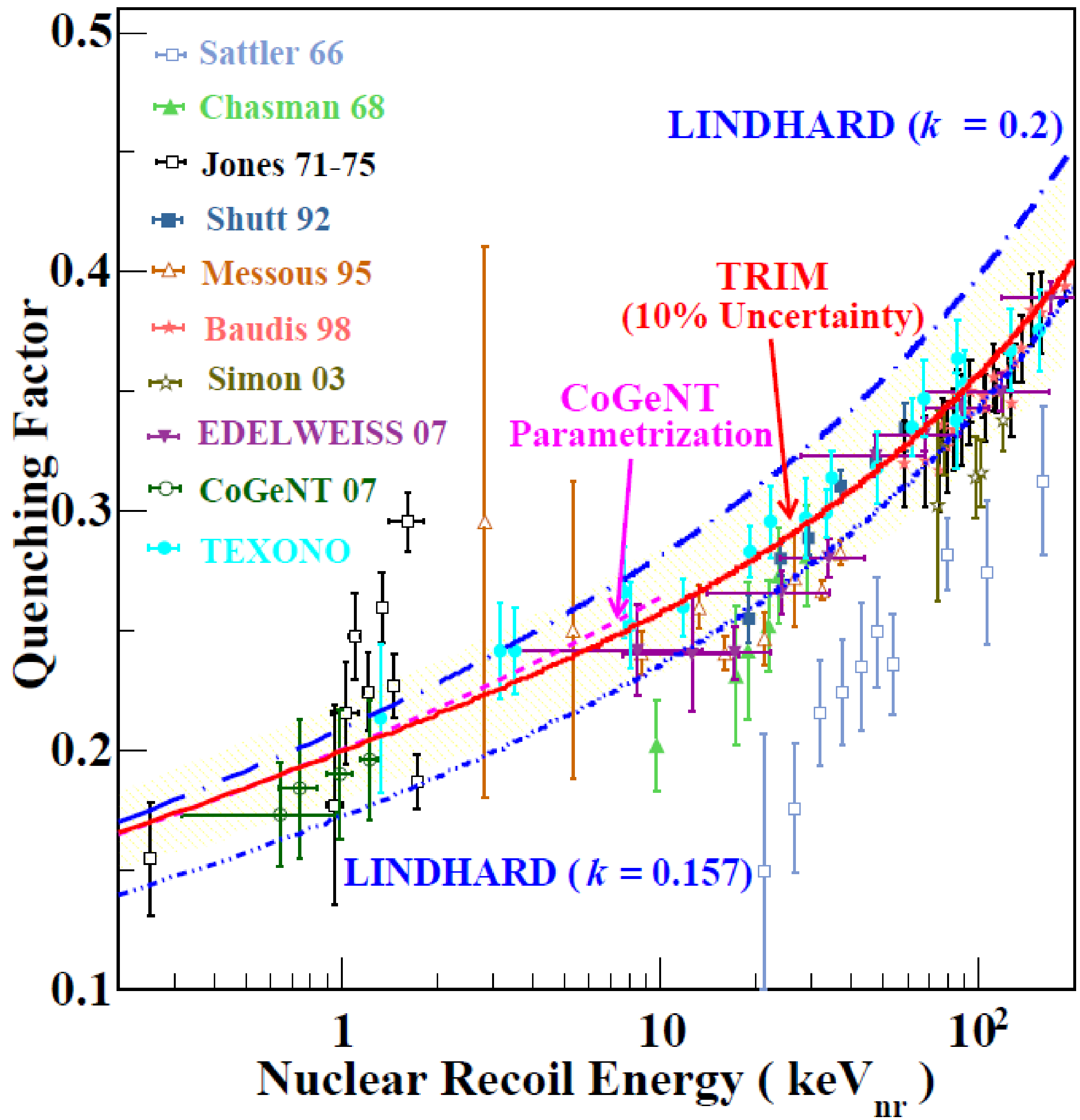
QF for Ge crystal

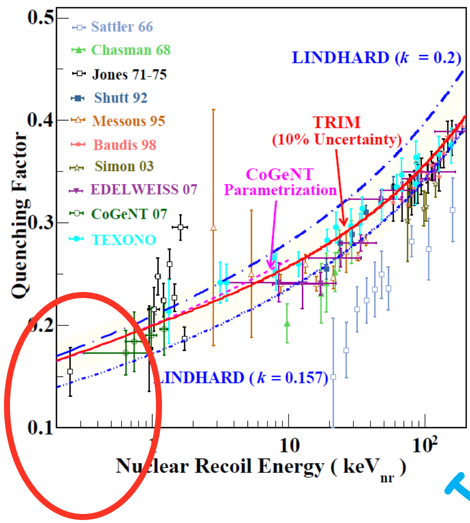


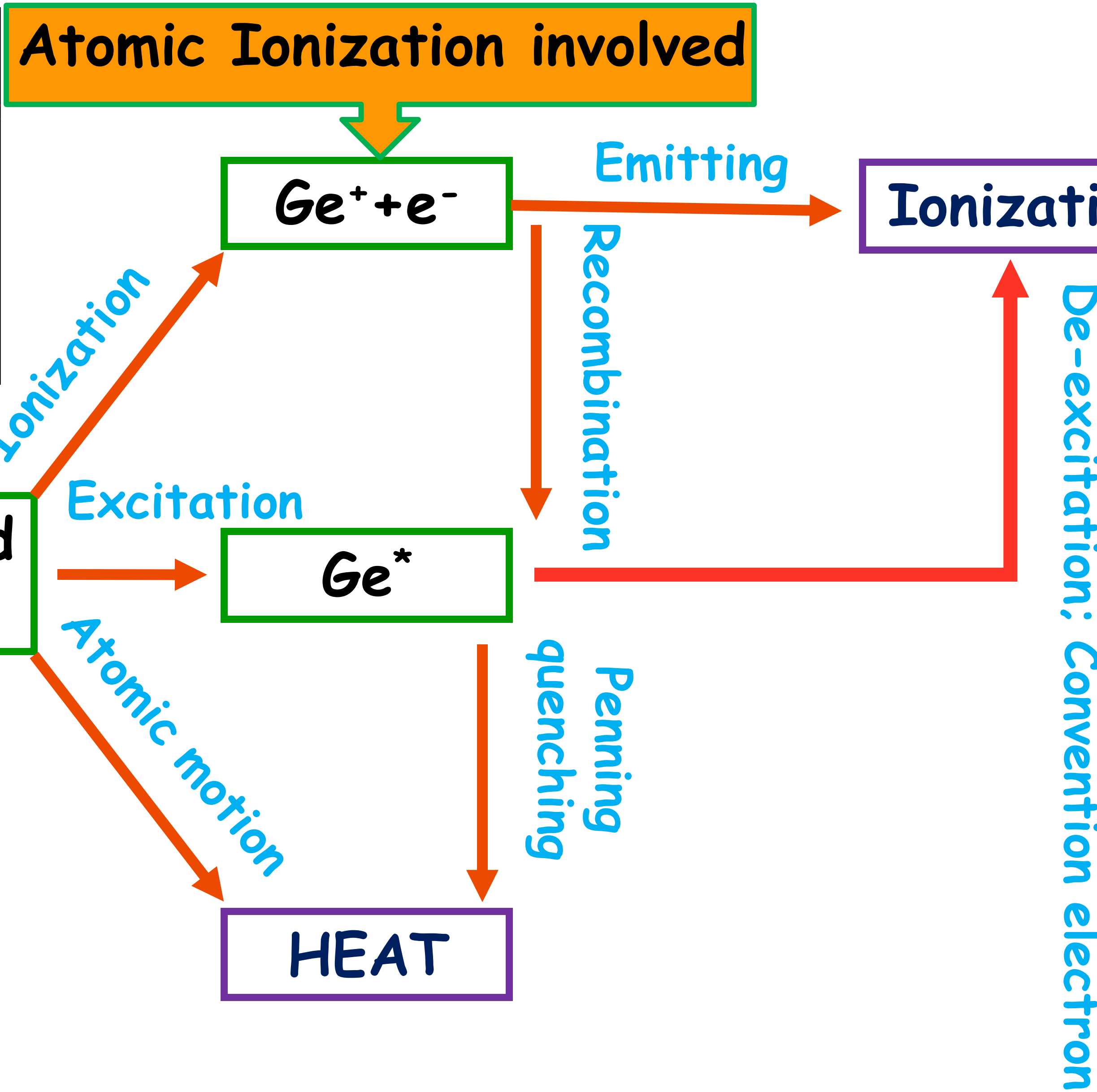
D. Barker and DM Mei [AP 2012]





A toy thought map

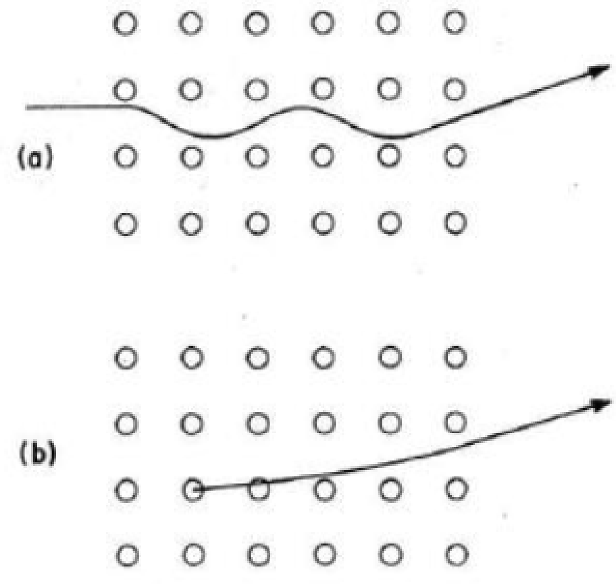




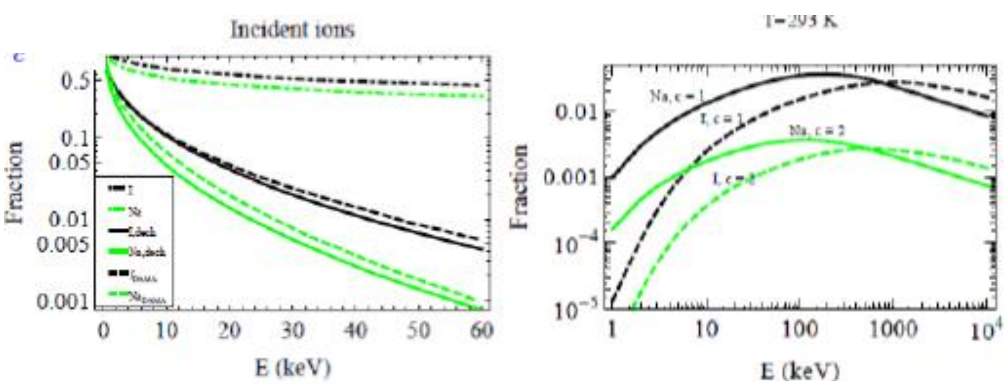
Channeling & Blocking Effects in Crystals

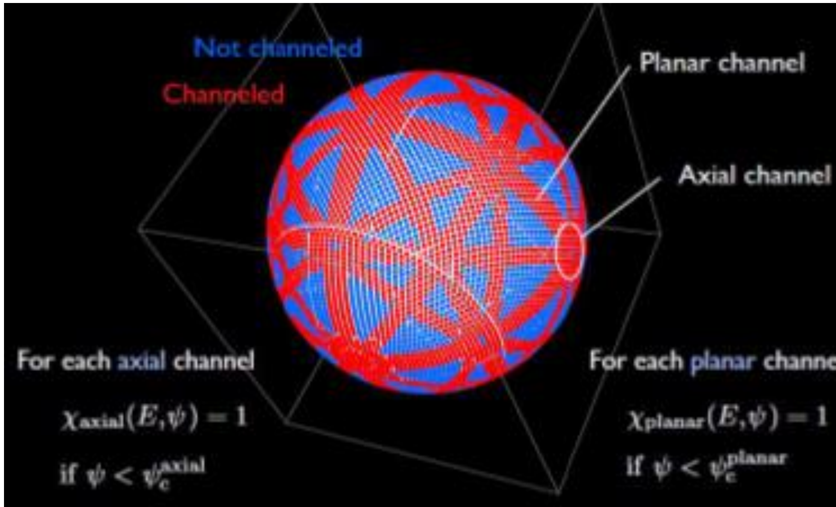
(a) Channeling:
Ions incident upon the crystal along symmetry axis and planes suffer a series of small-angle scattering that maintain them in the open "channels" and penetrate much further

(b) Blocking:
Reduction of the flux of ions originating in lattice sites along symmetry axis and planes



D. Gemmell 1974, Rev. Mod. Phys. 46, 129





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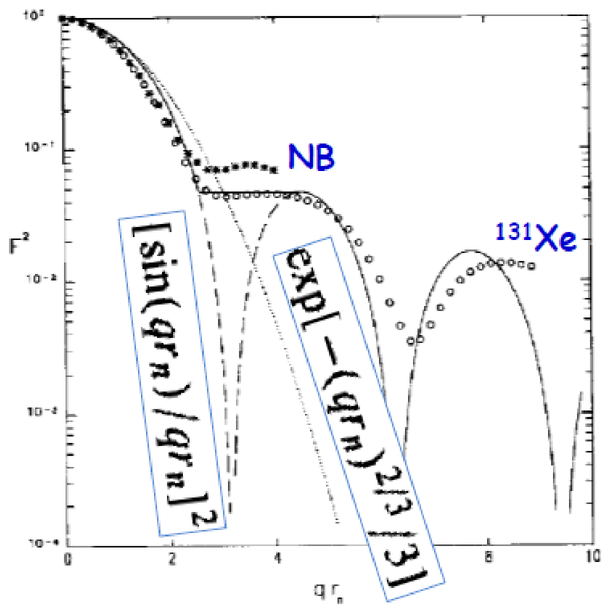
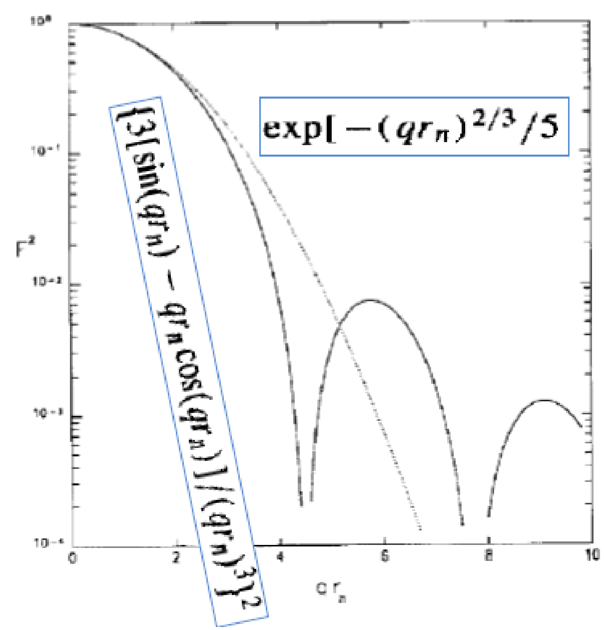
Bozorgnia, Gelmini, Gondolo
JCAP 1011 019 (2010)

Nuclear Form Factor

- ✓ The effective cross section decreases with the increasing momentum transfer q, while the wavelength h/q is not longer than the nuclear radius.
- ✓ In the first Born approximation, the form factor is the Fourier transfer of charge density.

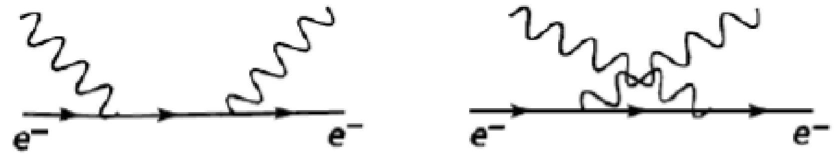
Thin Shell approximation (SD)
Solid Sphere approximation(SI)





QED interaction in Matter with low momentum transfer

Klein-Nishina



$$\left(\frac{d\sigma}{d\Omega}\right)_{KN} = \frac{r_e^2}{2}\left(\frac{\nu'}{\nu}\right)^2 \left\{\frac{\nu'}{\nu} + \frac{\nu}{\nu'} - \sin^2\theta\right\}$$

- The classical Compton formula can't stand due to the orbital electron effect.

- The modified Compton scattering is expressed

$$\frac{d\sigma_{aC}}{d\Omega} = \left(\frac{d\sigma_{KN}}{d\Omega}\right) S(x,Z)$$

Where the momentum transfer variable $x = \frac{1}{\lambda}\sin\frac{\theta}{2}$

✓ The interaction of rA->rAe may be more realistic than re->re at low q transfer.

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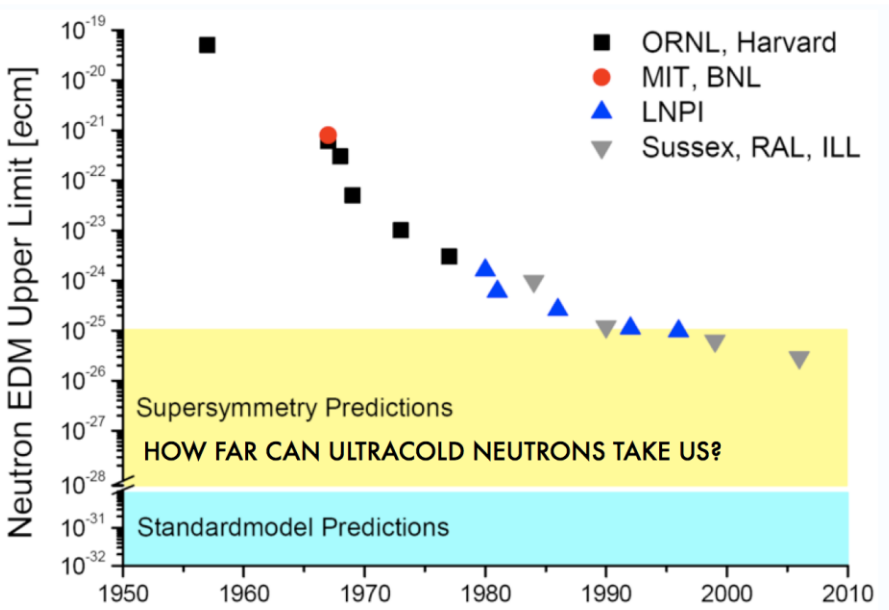
Axion was born

- ✓ Postulated by the Peccei-Quinn theory in 1977 as the psudo-Nambu-Goldstone boson to solve the strong CP problem in QCD.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{n_f g^2\theta}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi$$

A problem occurred at the end that are able to break CP system.

- ✓ Conflict with Expts from Neutron electric dipole moment



- A generic CP violation in strongly interaction sector would create EDM at ~10^{-18} e-cm.
- Present experimental limit : ~2×10^{-26} e-cm

Status of Axion

- ✓ The original Weinberg-Wilczek axion (Standard axion) has been ruled out.
- ✓ Invisible axions or more general "axion-like particles (ALPs)" were quickly constructed.
- ✓ Axions have not been observed successfully by experimental searches and astrophysical limits in principle.(Christian Beck argued that a signature consistent with a mass ~110 μeV)
- ✓ One of the leading cold-dark-matter candidates.
- ✓ Two mechanisms for invisible axion

1. **Hadronic models(KSVZ)** Hadronic axions are coupled to new, heavy quarks and do not interact with ordinary quarks and leptons at the tree level leading to a strong suppression of g_{Ae}.

2. **Non-hardronic axion models(DFSZ)** They couple to electrons at tree level, and this open axion production channels in stars.

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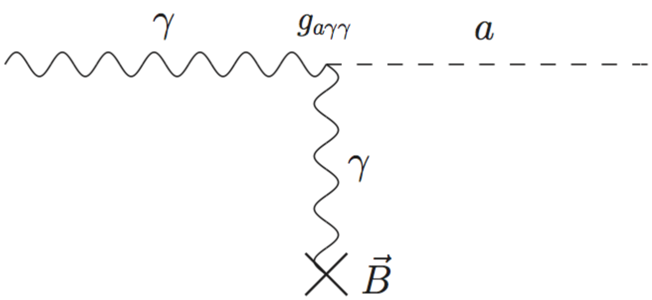
Axion from Sun



✓ **Primakoff production:**

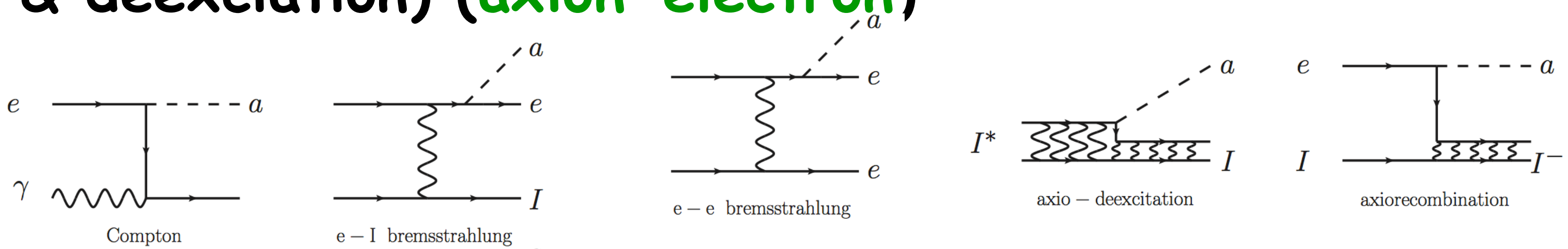
Produced by the inverse Primakoff conversion of thermal photons in the electromagnetic field of the solar plasma.

✓ M1 transition from ^{57}Fe (axion-nucleons)

1. Monochromatic axions of 14.4 keV emmited in M1 transition of ^{57}Fe with remarkable abundance in the Sun.

2. Low enough to be thermally excited in the hot interior.

✓ Compton, bremsstrahlung and axio-RD(recombination & deexciation) (axion-electron)



$$\frac{d\Phi}{dE} = \left(\frac{d\Phi}{dE}\right)^{\text{Compton}} + \left(\frac{d\Phi}{dE}\right)^{\text{bremsstrahlung}}$$

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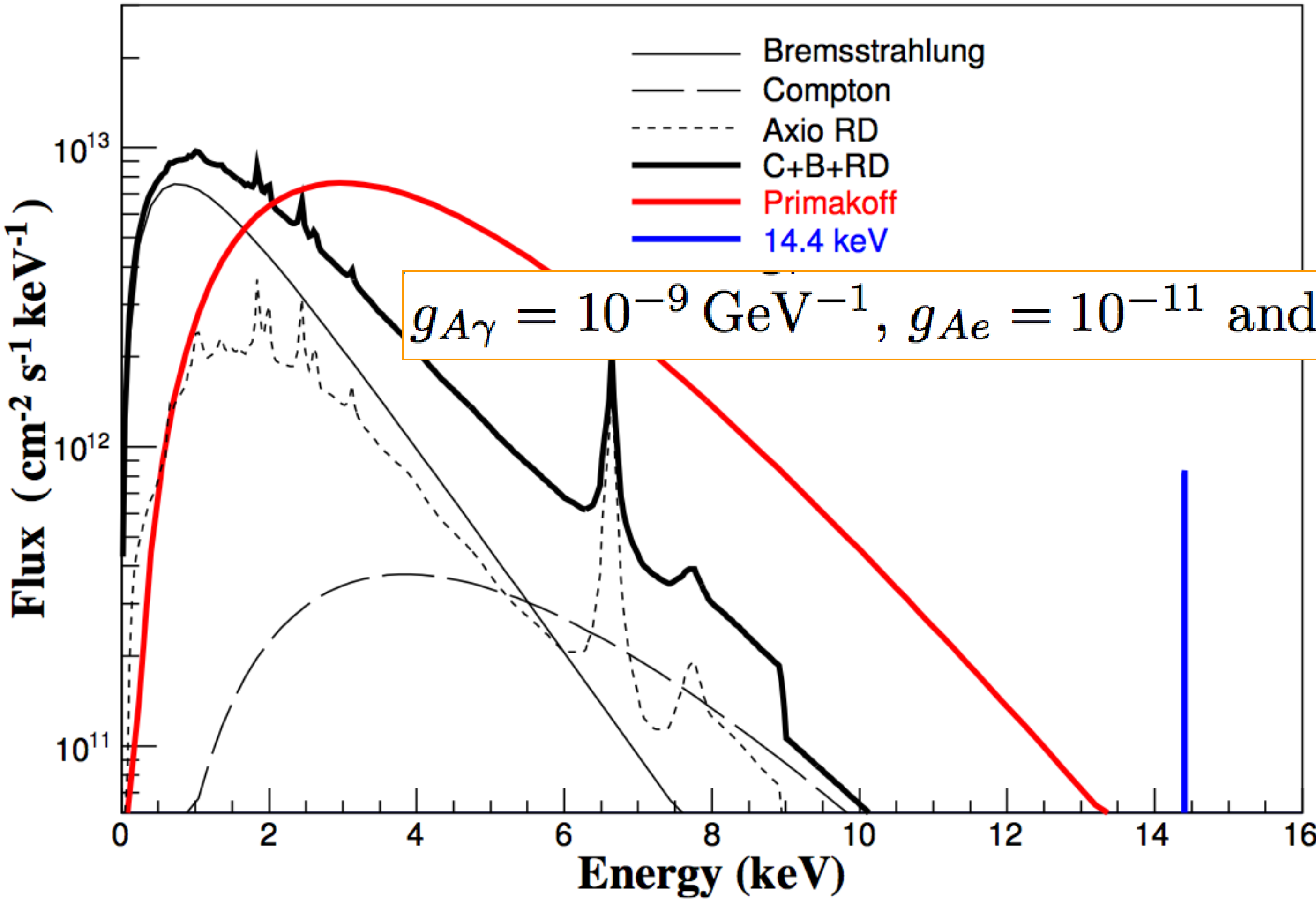
Expected axion flux from Sun



$g_{A\gamma} = 10^{-9}\,\mathrm{GeV}^{-1}$, $g_{Ae} = 10^{-11}$ and $g_{AN}^{\mathrm{eff}} = 10^{-7}$.

JCAP 11 (2013) 067; JCAP 05 (2013) 010

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✓ **Meanwhile, the non-relativistic ALPs can be one of the cold dark matter candidates.**

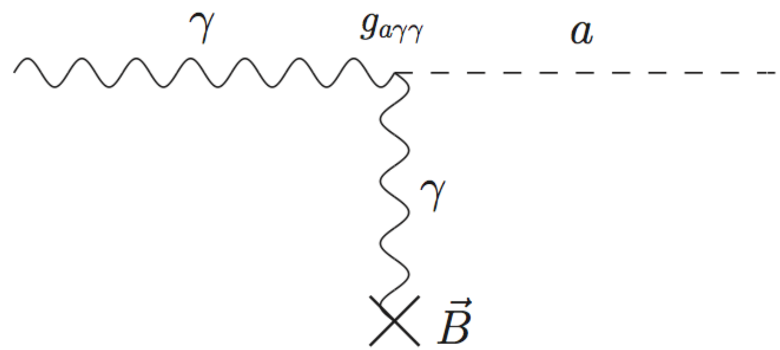
Axion detection

✓ Primakoff production:

It couples to E and B

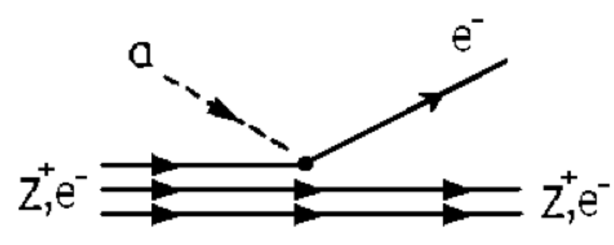
$$\mathcal{L}_{A\gamma\gamma} = \frac{G_{A\gamma\gamma}}{4} F_{\mu\nu}\tilde{F}^{\mu\nu}\phi_A = -G_{A\gamma\gamma}\mathbf{E}\cdot\mathbf{B}\,\phi_A$$

- Helioscopic (Tokyo, CAST)
- Microwave cavity(ADMX)
- Laser birefringence (PVLAS)
- Bragg diffraction scattering (SOLAX,COSME,CDMS,EDELWEISS)



✓ Axio-electric peoduction:

- XENON, EDELWEISS, CUORE, Derbin XMASS, CDMS, CoGeNT



Axioelectric
or Photoelectric-like

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Binned likelihood & least-square Mehtod

$$L=\prod_i e^{-N_i^{\rm th}}\frac{(N_i^{\rm th})^{N_i^{\rm exp}}}{N_i^{\rm exp}!}$$

Appr.

$$L=\prod_i \frac{1}{\sqrt{2\pi N_i^{th}}} e^{-\frac{\left(N_i^{\exp}-N_i^{th}\right)^2}{2N_i^{th}}}$$

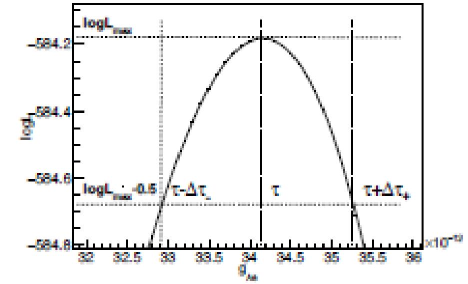
$$L=\prod_i \frac{1}{\sqrt{2\pi}\sigma_i^{\exp}} e^{-\frac{\left(N_i^{\exp}-N_i^{th}\right)^2}{2(\sigma_i^{\exp})^2}}$$

$$N_{C-B-RD}\left(\tilde{E}\right)=\int dE_A\left(\frac{dR_{axion}}{dE_A}\right)\times MT\frac{1}{\sqrt{2\pi}\sigma}\times e^{-\frac{\left(\tilde{E}-E_A\right)^2}{2\sigma^2}}$$

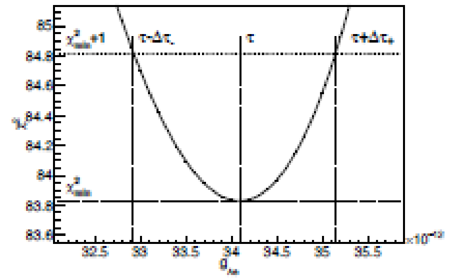
$$\equiv \lambda\times\bar{N}_{axion}\left(\tilde{E}\right)\quad \text{where } \lambda=f(g_{Ae})$$

$$N^{th}\left(\tilde{E}\right)=\lambda N_{axion}\left(\tilde{E}\right)+B\left(\tilde{E}\right)\qquad (\lambda=f(g_{Ae}))$$

$$N^{\exp}\left(\tilde{E}\right)=R^{\exp}\left(\tilde{E}\right)\cdot MT \qquad \sigma_i^{\exp}=\sigma_i\bullet MT$$



$$\chi^2=\sum_i\frac{\left(R_i^{\exp}-R_i^{th}\right)^2}{\sigma_i^2}$$



$$R^{th}\left(\tilde{E}\right)=\lambda R_{C-B-RD}\left(\tilde{E}\right)+B_R\left(\tilde{E}\right)\qquad (\lambda=f(g_{Ae}))$$

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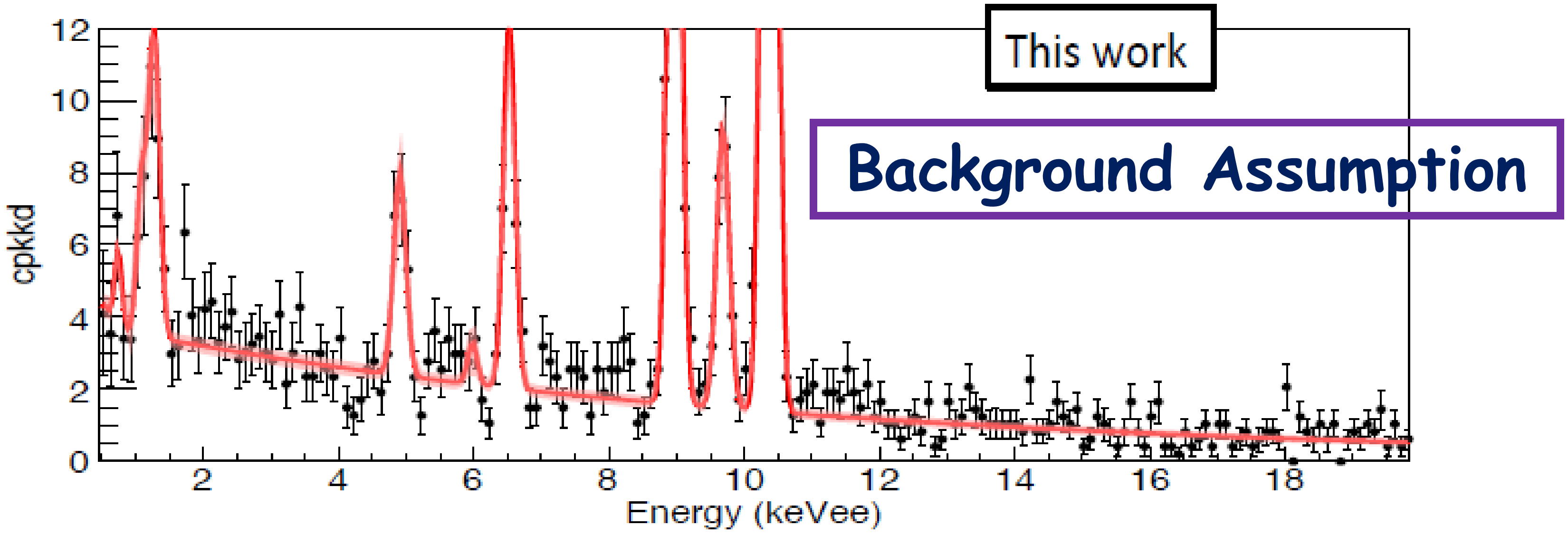
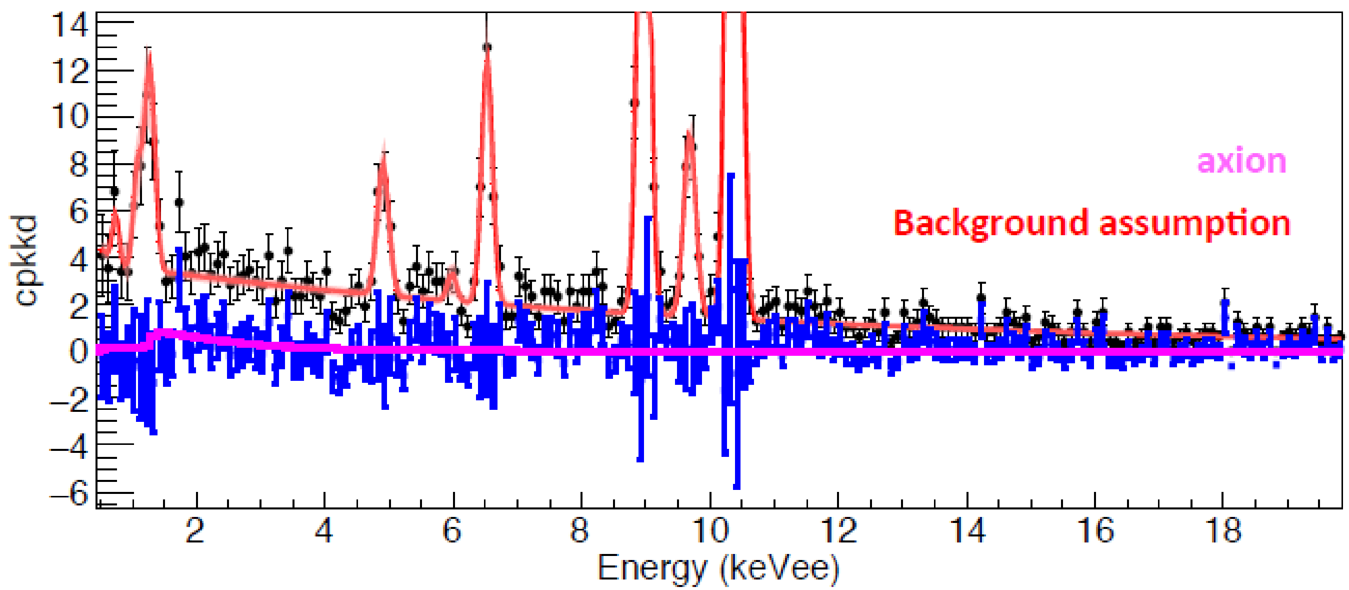
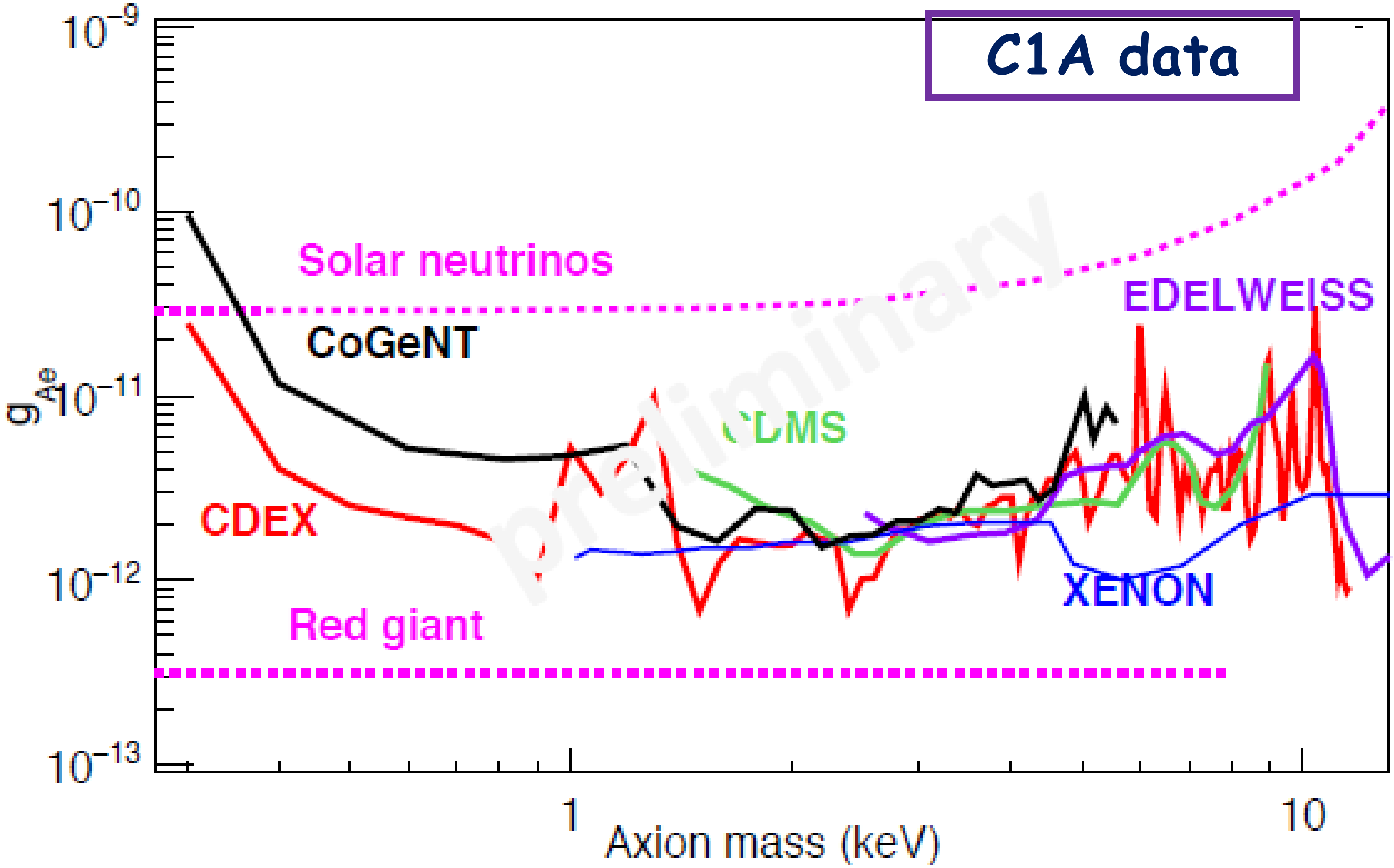
Data Analysis





Preliminary result for APLs as DM searches



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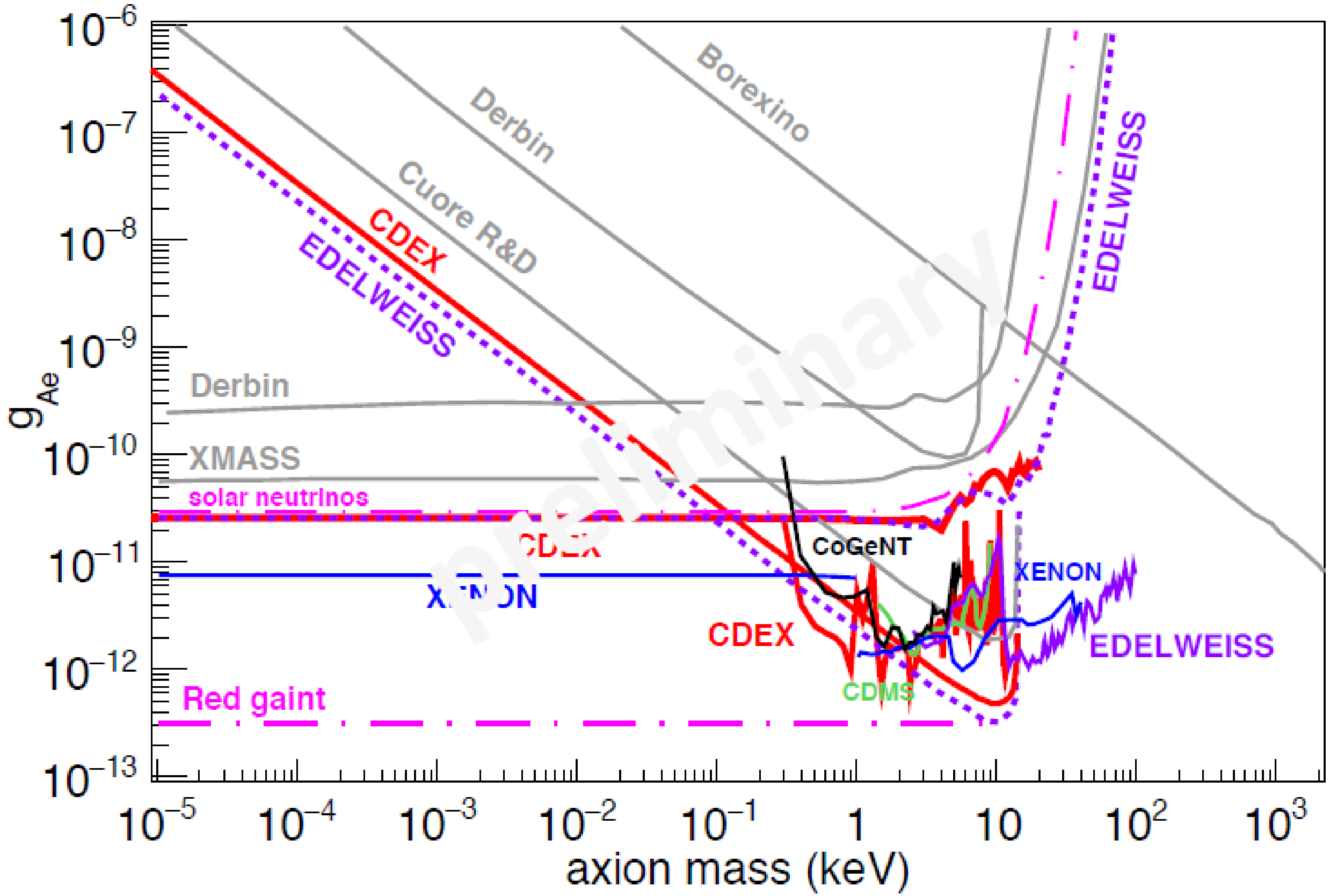
Preliminary result for g_{Ae}



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Outlooks & Prospects

- ✓ Nuclear & Atomic Physics plays an important role both in detector response models and detection channels beyond the "standard" detection.
- ✓ The recoil energy for Direct Detection of Dark Matter searches lies on the atomic physics region.
- ✓ Probing the axion dark matter has been studied.
- ✓ Quenching factors/light yields at low energy region is crucial.
- ✓ Understanding low energy background strongly depends on the understanding of Nuclear/Atomic Physics.
- ✓ Opening new detection channels are pursuing.