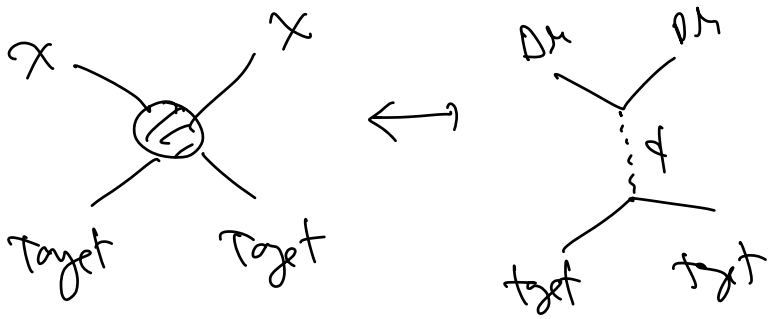
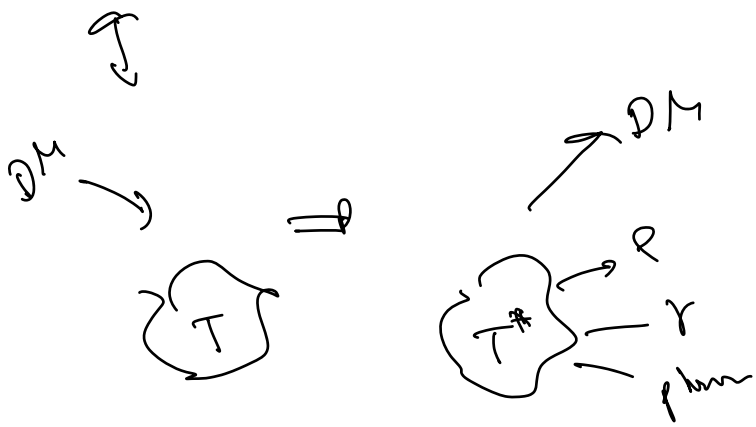
DARK MATTER ⑤ - GGI '22 [don't hockey. trust]

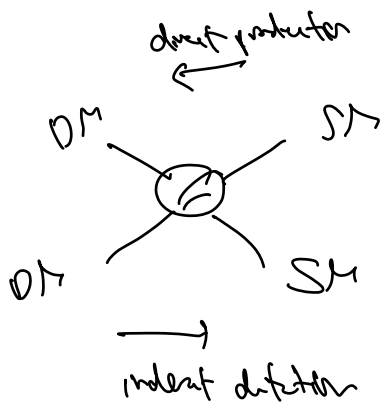
Direct Detection of DM:

DM interact w target in the lab (typically underground)



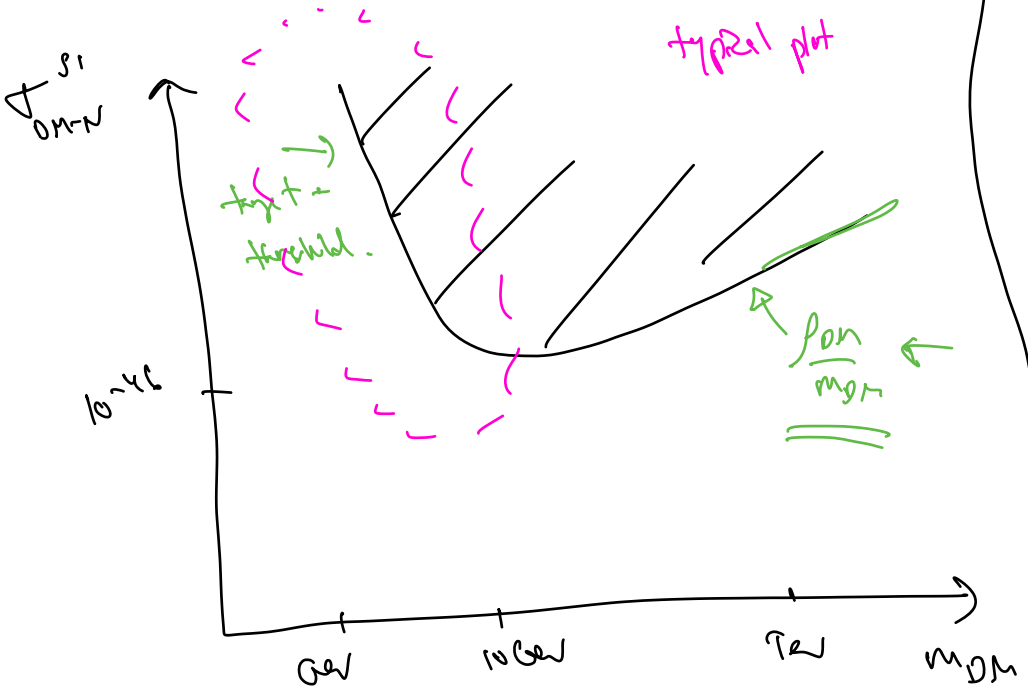


WIMP:



↑ Direct detection

Many exp. searching in this way for DM - (Xenon1T, PandaX, CRESST, DarkSide, DAMIC, CDMS, LUX, ⋮)



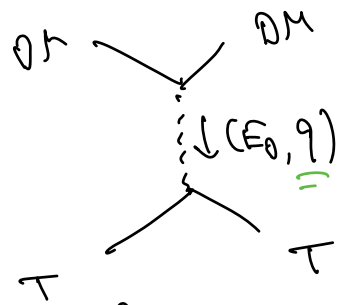
$$\text{Rate} \sim \frac{1}{f_T} \cdot (\text{DM flux}) \cdot \text{target property} \cdot \sigma_{nT}$$

$(\text{DM flux}) \sim n_{DM} v \sim \frac{\rho_{DM}}{m_{DM}} \int d^3v\, f(v)$; $\int d^3v\, f(v) \sim 10^{-3}$ (velocity dispersion)

$f(v)$ typically Standard Halo model -

$$\begin{cases} f_{MB}(v_x) = \dfrac{4\pi v_x^2}{N_E} e^{-v_x^2/v_0^2}\, \Theta(v_{esc} - v_x) \\ v_0 \sim 220\ \text{km/sec}, \quad v_{esc} \sim 500\ \text{km/sec} \\ \rho_{DM} \sim 0.3\ \text{GeV/cm}^3 \end{cases}$$

Experiments typically look for Nuclear Recoils (NR):



$$E_{NR} = \frac{q^2}{2m_T} \sim \frac{(m_X v)^2}{2m_T} \sim \text{keV}\left(\frac{m_X}{100\,\text{MeV}}\right)^2 \left(\frac{30\,\text{GeV}}{m_T}\right)$$

$\Rightarrow E_{th} \sim$ keV

for $m_X \sim 30$ GeV, $E_{NR} \sim$ 2keV, great ☺

Not great for sub-GeV masses.

⇒ understand through billiard balls:

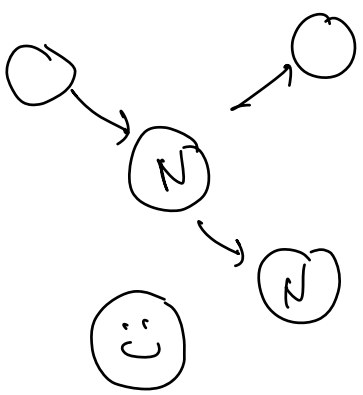
WIMP - large ball ≠ light DM - as we saw is generic

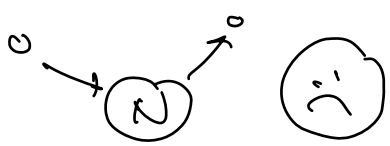
for many mechanisms -

Kinematics like ping pong ball

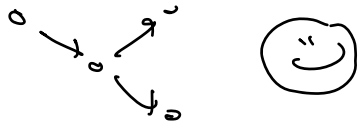
trying to hit a heavy bowling

ball - can't work



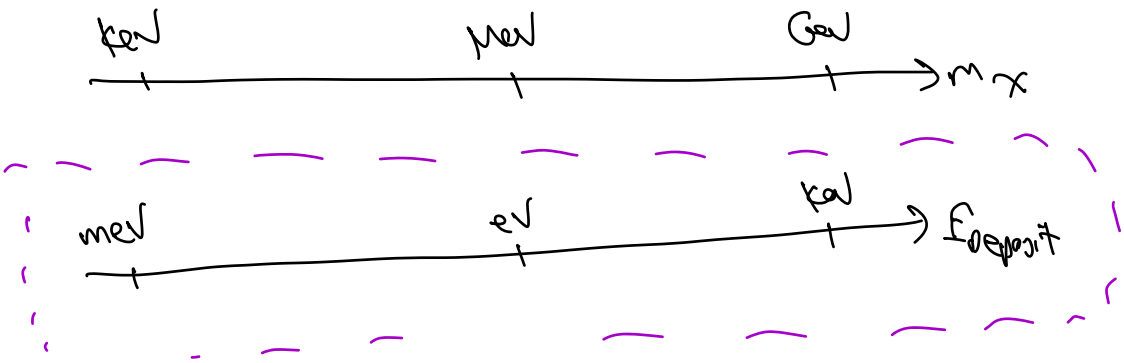


⇒ Smarter to scatter off of something lighter — electrons!

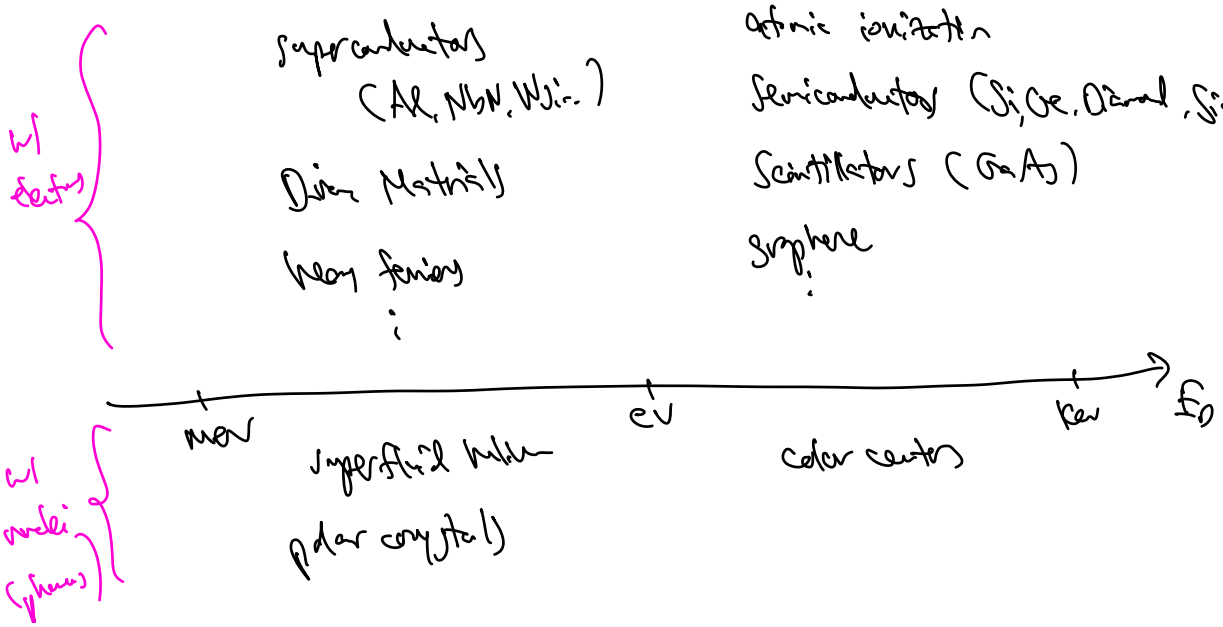


⇒ Basic idea behind most ideas in the literature.

⇒ Energy deposition: $\text{scatter} \sim E_{D\,max} = \text{entire kinetic energy} \sim m_\chi v^2 \sim 10^{-6} m_\chi$



organize all ideas based on E_D:



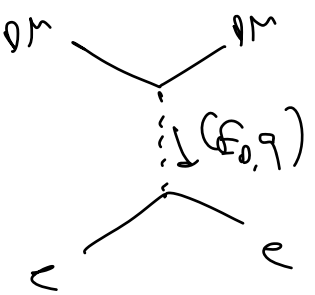
Work through a few - get a taste of materials / methods / processes / detection philosophies.

Scenario (I): in Ref of σ_{ion}, typically written as reference xsec, times a fun factor:

$$\bar{\sigma}_e \cdot |F_{DM}|^2$$

↑ xsec @ fixed reference momentum transfer $q_{ref} \sim \alpha m_e$ (typical in semiconductors)

↖ correct for momentum dependence:



$$\text{propagator} \sim \frac{1}{m_\phi^2 - q^2} \overset{(F_D \ll q)}{=}$$

$$|F_{DM}(q)|^2 = \begin{cases} 1 & m_{\phi} \gg \alpha m_e \quad \text{heavy mediator} \\ \left(\frac{\alpha m_e}{q}\right)^2 & m_\phi \ll \alpha m_e \quad \text{light mediator} \end{cases}$$

often see results / projected reach for each heavy/light med.

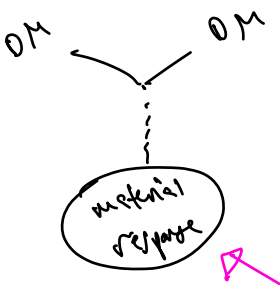
Sidenote (II): Rate & target properties -

historically computed by overlap of single particle excitation wave functions.

Now accurate & general way that automatically accounts for all many-body effects of the material -

Dielectric function $\longleftrightarrow$ loss function

$$\mathrm{Im}\left(-\frac{1}{\epsilon(q,\omega)}\right)$$

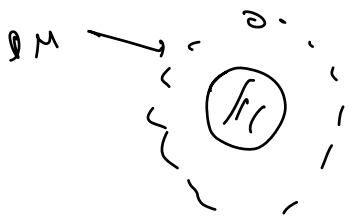


Response of the system to a weak probe!

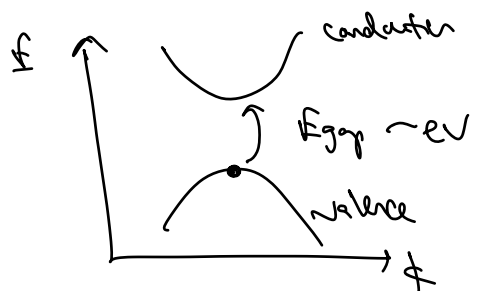
measure! [Yi et al PRL 2101.08263]

Includes plasmons - optical materials via energy matching

Ex #1: Eight ideas - atomic ionization (semiconductors)



[Essig et al 2012]

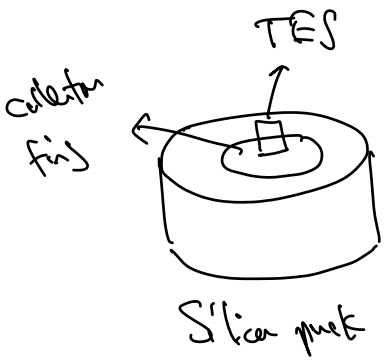


[1909.01598 Derkaj]

$E_{th} \sim 10\,eV$
(Xenon)

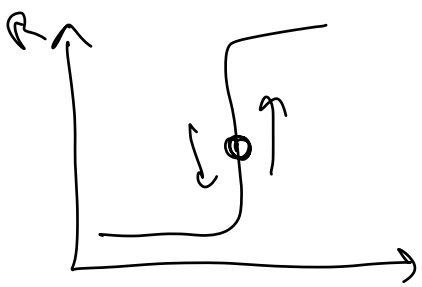
$\Rightarrow m_\chi \gtrsim MeV$

E.g. SENSEI & SuperCDMS: Excitation semiconductor physics -
Excitations picked up and - collect & detect.



Technology - TES:
Transition Edge Sensor

Superconductor - bolometer



decode effect of signal → resolution in exp. T

what about $m < MeV$??

Ex. #2: Superconductors: ground state = Cooper pairs
Binding energy (= gap) = $O(meV)$

$\Rightarrow m_\chi \gtrsim keV$

DM comes in, scatters on Cooper pairs, breaks them - excites, collect & detect.

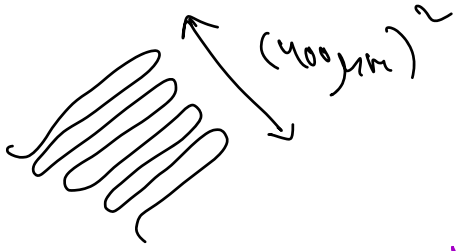
Bulk - Similar in spirit to SuperCDMS [1004.07277]

Target + sensor philosophy: [PRL 1907.05101 + 2110.01138]

SNSPD = superconducting nanowire single photon detector.

mature technology of QIS!

nanowire in superconducting (SC) state, clyx to critical current, E_D → creates a hotspot - e's diffuse away - R area across the nanowire — voltage pulse.

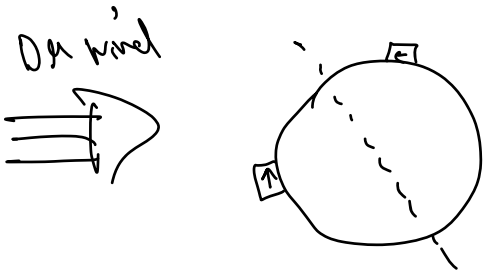


Apply this for DM! target + sensor.

E_{th} = 125 meV!

prototype 4.3 ng, 3 hours - strongest limits! (0.8 eV)

Ex #3: Directional information - daily modulation has been recognized as powerful tool for direct detection: separates signal from background:



≠ primary electron - 2D target (graphene):

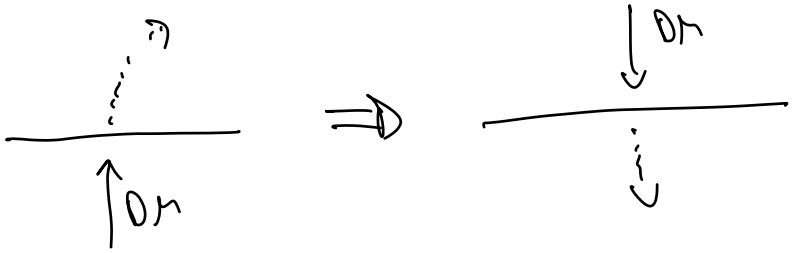
(primary interaction)

$E_{ejected} \sim O(eV)$

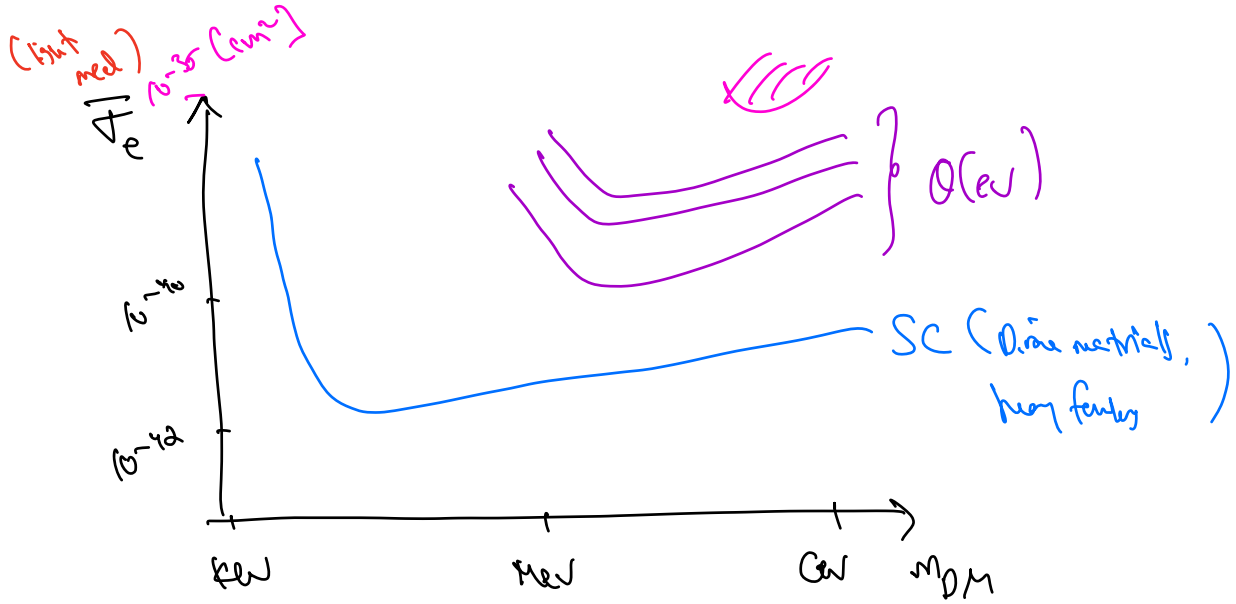
$\Rightarrow m_\chi \gtrsim$ MeV

Ejected electron traces the direction of the incoming DM particle.

$\Rightarrow$ Forward-Backward discrimination power:



[PTOLEMY exp!] [1606.08849]

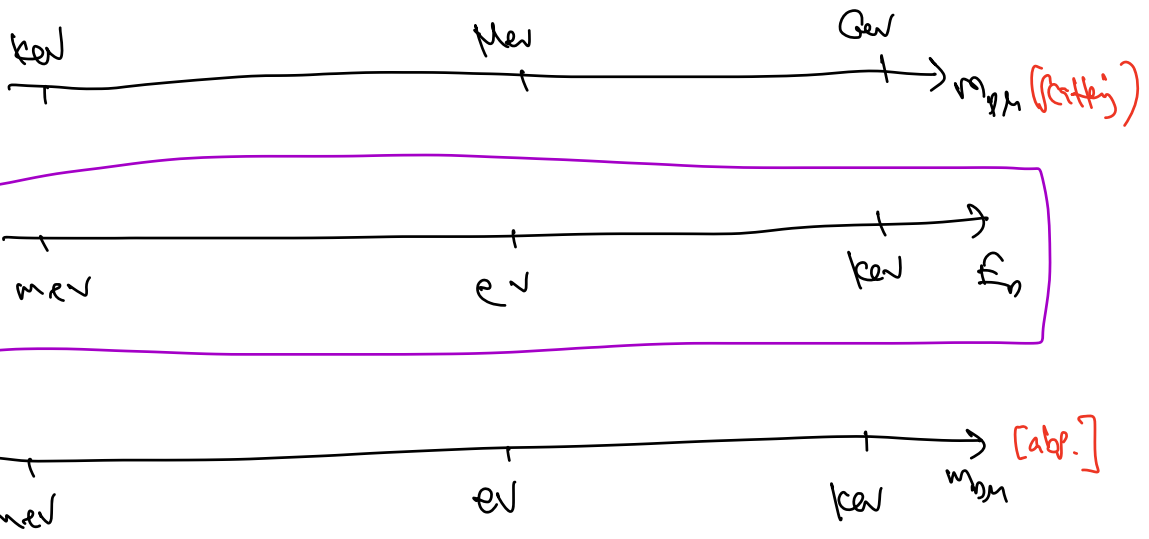


2 for the price of 1 :

any target material can go further:

+ absorption!

no cutoff in DM - $E_D \sim m_{DM}$



⇒ Summary:

DM is exciting ! mechanisms
models
ways to detect.

looking forward to your next big DM idea!!

Thanks