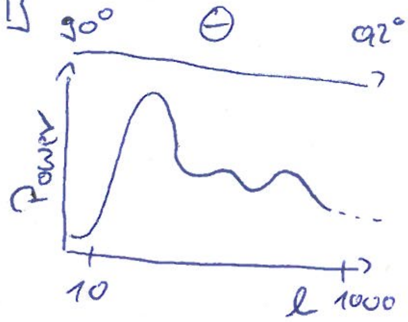
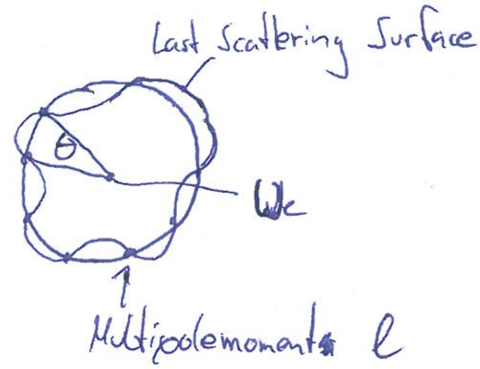
Dark Matter Indications

Script: arXiv: 1509.08767

Ludwig Rauch

- CMB





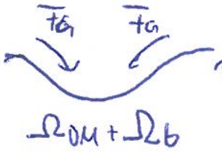
→ Baryonic acoustic oscillations

- Consider $\Omega_m = \Omega_{DM} + \Omega_B$

  Ω_r

- Oscillations driven by radiation pressure and gravity

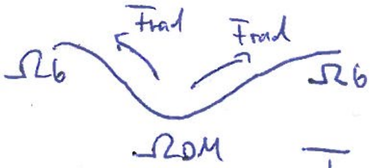
1.



Grav. potential (seeds by Inflation)

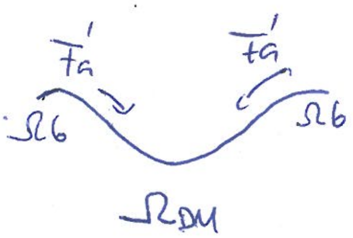
⇒ F_{rad} increases due to high pressure

2.



F_{rad} only affects Ω_B NOT Ω_{DM}

3.



F_G' now dominated by Ω_{DM}

⇒ Differences between odd and even peaks constraints Ω_b and Ω_{DM}!

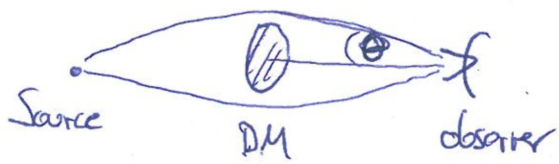
- Structure formation

  → From Simulation (e.g. Aquarius, Illustris, ...)

  → Constraints on free streaming length

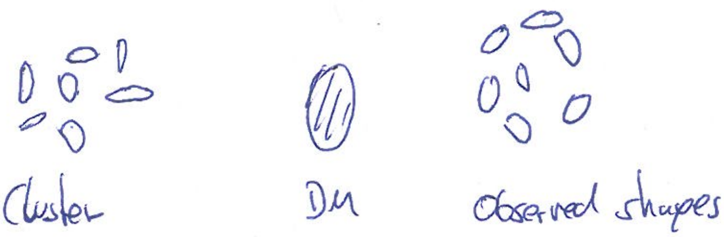
- Gravitational lensing

  - Strong lensing



$$\Theta = \sqrt{\frac{4GM}{r_c^2}}$$

  - Weak lensing



- Rotation curves:

  - Expectation: $F_G = \frac{GmM}{r^2}$ $\qquad F_r = \frac{m v_c^2}{r}$

$$\Rightarrow v_c(r) = \sqrt{\frac{G M(r)}{r}}$$

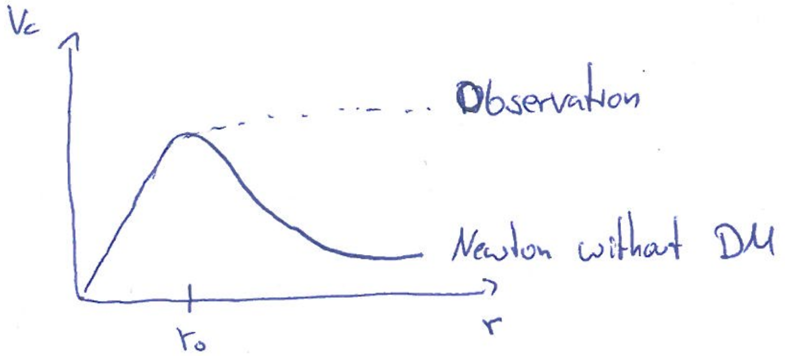
assume $\rho = \text{const}$

$$\Rightarrow v_c(r < r_0) = \sqrt{\tfrac{4}{3}\pi G \rho} \cdot r$$

$$v_c \propto r$$

$$\Rightarrow v_c(r > r_0) = \sqrt{\frac{GM}{r}}$$

$$v_c \propto \sqrt{\frac{1}{r}}$$



Fix: $v \propto \sqrt{\frac{M}{r}}$ thus $M \overset{!}{\propto} r$ so v is const. for $r > r_0$

Since $V \propto r^3 \Rightarrow \rho_{DM} \propto \frac{1}{r^2}$

density of dark matter halo

→ needs particle?

Or! Newtons law a problem?

→ Modified newtonian dynamics (MOND)

Idea: $F = m \cdot a \rightarrow F = m \cdot a \cdot \mu\left(\frac{a}{a_0}\right)$

with $\mu\left(\frac{a}{a_0}\right) \simeq 1$ if $\frac{a}{a_0} \gg 1$

$\mu\left(\frac{a}{a_0}\right) \approx \frac{a}{a_0}$ if $\frac{a}{a_0} \ll 1$

then: $\mu\left(\frac{a}{a_0}\right) \cdot a = \frac{GM}{r^2}$ with $F_G = \frac{GmM}{r^2}$

if $r > r_0 \rightarrow \mu\left(\frac{a}{a_0}\right) \simeq \frac{a}{a_0}$

$\Rightarrow \frac{a^2}{a_0} = \frac{MG}{r^2}$ with $a = \frac{v^2}{r}$

$\Rightarrow v = \sqrt[4]{M G a_0}$ thus $v \approx$ const for $r > r_0$

- Particle Dark Matter

→ Can not be SM particles

- WIMP (Weakly interacting massive particles)

Motivation:

under general assumptions $\Omega_\chi \propto \frac{1}{\langle\sigma v\rangle} \sim \frac{m_\chi^2}{g_\chi^4}$

mass

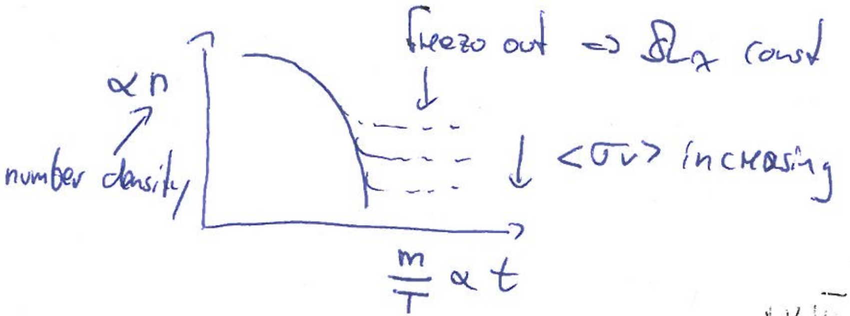
relic density

thermally averaged annihilation cross section

coupling

if: $m_\chi \sim M_{Weak} \sim 100\,\mathrm{GeV} - 1\,\mathrm{TeV}$
$g_\chi \sim g_{Weak} \sim 0{,}65$ $\Big\} \Rightarrow \Omega_\chi \approx 0{,}23$

Very close to our observation



$\psi\bar{\psi} \leftrightarrow \chi\bar{\chi}$

Add Boltzmann equation !!

$$\frac{dn_\psi}{dt} = -3Hn - \langle\sigma_{ann} v\rangle (n^2 - n_{eq}^2)$$

equilibrium number density

$Y = \frac{n_\psi}{s}$

$x = \frac{m}{T}$

Sterile ν

- Add right-handed ν to SM

  $\rightarrow$ Allow oscillation of active to sterile ν

$$\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} = \begin{pmatrix} \cos(\theta_0) & \sin(\theta_0) \\ -\sin(\theta_0) & \cos(\theta_0) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P(\nu_L \rightarrow \nu_R ; t) = |A(\nu_L \rightarrow \nu_R ; t)|^2$$

with $\underset{\substack{\uparrow \\ \text{transition amplitude}}}{A}(\nu_L \rightarrow \nu_R ; t) = \langle \nu_R | \nu(t) \rangle$

$$P(\nu_L \rightarrow \nu_R ; t) = \sin^2(2\theta_0) \sin^2\left(\frac{\Delta m}{\Delta E} \cdot t\right)$$

with $\Delta m^2 \approx m_2^2 - m_1^2$

- <u>might</u> explain reactor anomaly
- <u>might</u> solve ν hierarchy problem
- <u>might</u> account for DM

Axion

$$\mathcal{L}_{QCD} \subset \frac{\theta g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$ ← gluons

$$\bar{\theta} = \theta - \arg(m_1, m_2 \ldots m_n)$$

↑ Quark masses

Strong CP Problem: $\bar{\theta} \neq 0 \Rightarrow$ QCD violates P and CP

→ from theory expected

However: $\bar{\theta} < 10^{-9}$ why so small?

↳ measured from the electric dipole moment of the neutron

Solution: Predict new quasi-symmetry $U_{PQ}(1)$

→ Must be spontaneously broken

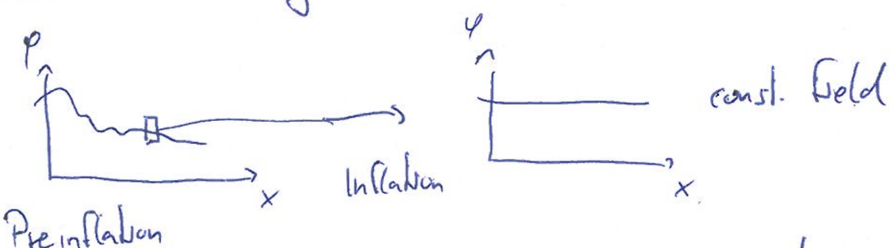
→ Goldstone boson: axion

$$\Rightarrow \bar{\theta} = \theta - \arg(m_1 \ldots m_n) - \frac{a(x)}{f_a}$$

$a(x)$ ← axion field

f_a ← axion decay const

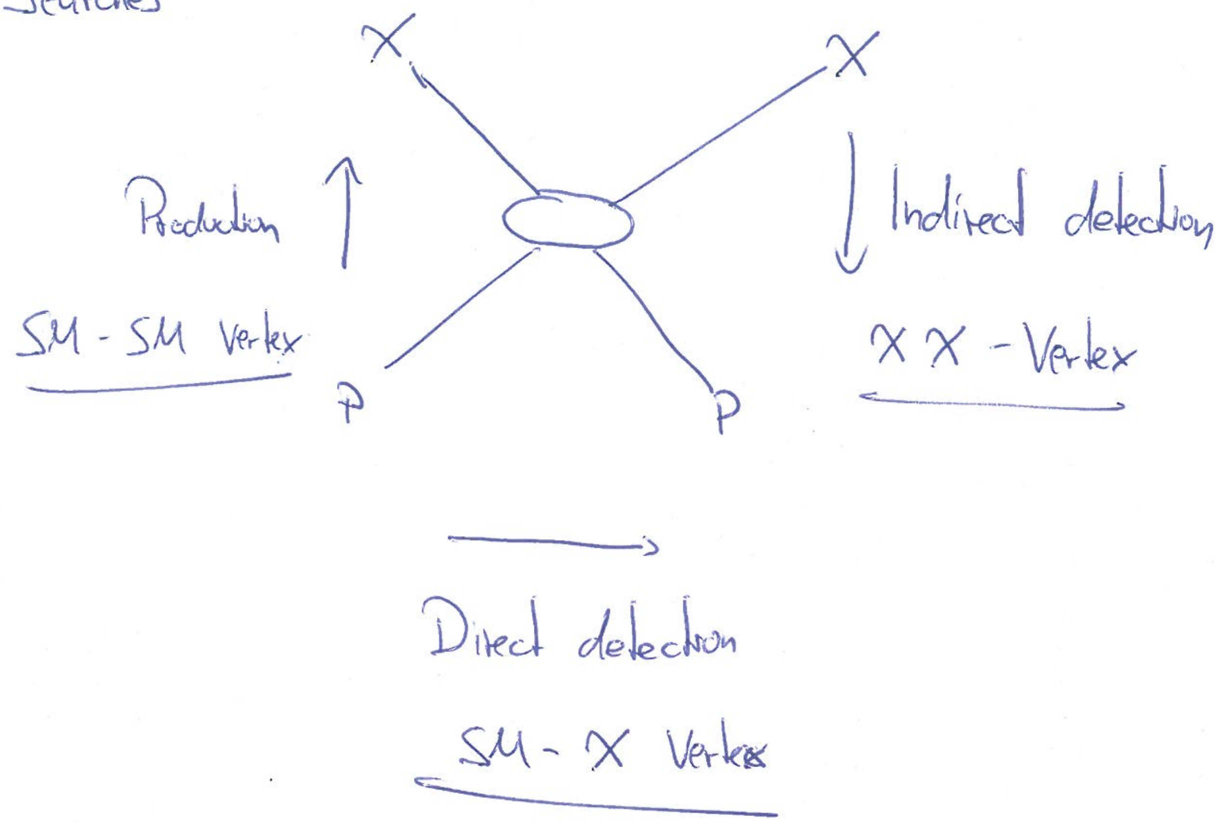
Production: Misalignment mechanism



time evolution given by: $\Box\varphi + m^2\varphi = 0$

solution for flat field: Damped harm. oscillator → can produce very "cold" axions!

Searches



Production: eg: $pp \to \chi\bar{\chi} + X$ @LHC

- often missing p_T analysis ("mono-objects")
- can't proove stability of χ

Indirect detection: - Look at objects where m_χ is grav. accumulated
→ center of galaxy; satellite galaxies; Sun ...

neutral eg: $\chi\chi \to \gamma\gamma, \gamma Z, \gamma H$ Newton, Fermi, Hess ..

charged $\chi\chi \to q\bar{q}, W^+W^-$ and further $\underbrace{e^+ e^- / p^+ p^-}_{\text{AMS, Pamela}}$ / ν's

↑ Superk
IceCube

Ludwig Rauch

Signatures of dark matter

$$\frac{dN}{dt} = \sigma \cdot \mathcal{L}$$

particle physics

Luminosity given by astrophysics

$$\mathcal{L} = N_T \cdot F$$

target atoms

Flux

$$F = n_\chi \langle v \rangle$$

average velocity

particle density of dark matter in Halo $n_\chi = \frac{\rho_0}{m_\chi}$

local density

mass

$$\Rightarrow \frac{dN}{dt} = \sigma \cdot N_T \cdot \frac{\rho_0}{m_\chi} \langle v \rangle$$

- we are interested in the energy spectrum!
- normalize to the target

$$\Rightarrow \underbrace{\frac{1}{M_T} \frac{dN^2}{dE\,dt}}_{=: \frac{dR}{dE}} = \frac{d\sigma(E_{nr}, v)}{dE_{nr}} \cdot \frac{\rho_0}{m_\chi} \cdot \langle v \rangle \cdot \frac{1}{m_N}$$

$$\left[\frac{\#}{\mathrm{kg} \cdot \mathrm{d} \cdot \mathrm{keV}} \right]$$

- Introduce velocity distribution of dark matter $f(v)$

$$\Rightarrow \frac{dR}{dE} = \frac{\rho_0}{m_N m_\chi} \int_{v_{min}}^{v_{max}} v \cdot f(v) \cdot \frac{d\sigma(E_{nr}, v)}{dE_{nr}} \cdot dv$$

with: $V_{min} = \sqrt{\frac{m_A E_{thr}}{2\mu_A^2}}$ ← Energy threshold of detector

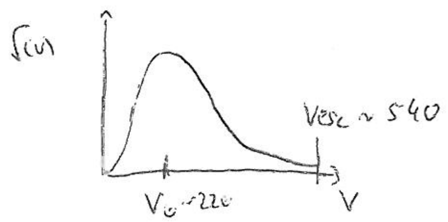
↑ reduced mass of m_χ and m_A

$f(v)$ given by Maxwell-Boltzmann distribution (neglect time dependence here)

$$f(v) = \underbrace{\frac{1}{N}}_{\text{Normalization}} \cdot \left(e^{-\frac{v^2}{v_0^2}} - \underbrace{e^{-\frac{v_{esc}^2}{v_0^2}}}_{\text{truncated at } v_{esc}} \right)$$

V_0 → approx. circular velocity $\sim 220 \frac{km}{s}$

V_{esc} → escape velocity of DM particles in Milky Way $\sim 540 \frac{km}{s}$



1. Use information of the spectral shape:

$$\frac{dR}{dE} \approx \underbrace{\left(\frac{dR}{dE}\right)_0}_{\text{event rate at zero momentum}} F^2(E) \cdot e^{-\frac{E}{E_c}}$$

F ← Form factor; E_c ← constant dependent on target

⇒ recoil energies $\mathcal{O}$(keV) → implication for energy threshold of the detector

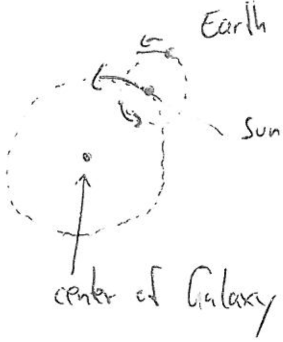
2. Annual-modulation → exploit time dependence

$f(v, \underline{t})$

$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E) \cdot \cos\left(\frac{2\pi(t-t_0)}{T}\right)$$

Time averaged rate

modulation amplitude



3 "Directional signal"

$$\frac{dR}{dE\, d\cos\gamma} \propto \exp\left[-\frac{[(v_E + v_0)\cos\gamma - v_{min}]^2}{v_c^2}\right]$$

γ defined by the direction of the nuclear recoil relative to the mean direction of the solar motion

- Cross section – Nuclear physics / Particle physics

$$\frac{d\sigma}{dE_n} = \frac{m_A}{2\mu_A^2 v^2}\left(\sigma_0^{SI} F_{SI}^2(E) + \sigma_0^{SD} F_{SD}^2(E)\right)$$

→ split in spin-independent and spin-dependent interactions

$$\Rightarrow \mathcal{L} \supset \underbrace{\alpha_q^S \chi\bar{\chi} q\bar{q}}_{\text{Scalar - Scalar}} + \underbrace{\alpha_q^V \bar{\chi}\gamma_\mu \chi \bar{q}\gamma^\mu q}_{\text{Vector - Vector}}$$

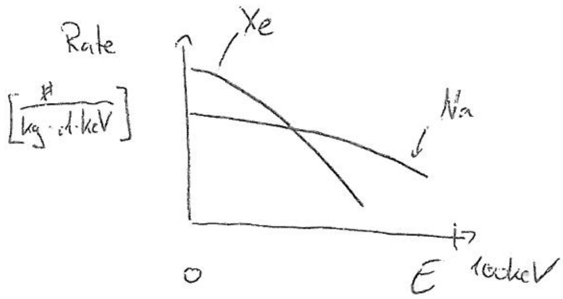
SI: $\sigma_0^{SI} = \sigma_p \frac{\mu_A^2}{\mu_p^2} \left[Z f^p + (A-Z) f^n \right]^2$ → from scalar part!

reduced mass of proton und χ — coupling to proton and neutron

if $f_p = f_n$

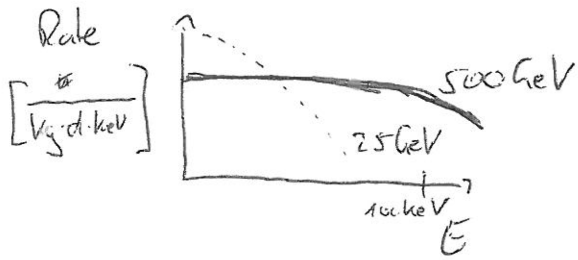
$\Rightarrow \sigma_0^{SI} \propto A^2$

- much stronger than vector-vector interaction
- Strong implication for detectors!
  ↳ choice of target



$m_A(Xe) \gg m_A(Na)$

- A^2 enhancement
- Formfactor suppresses higher momentum transfers (~ coherence loss)



Same target

- Energy threshold is very important for low mass WIMP searches

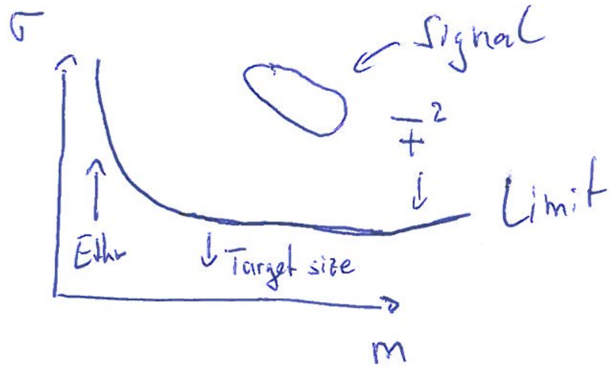
Ludwig Rauch

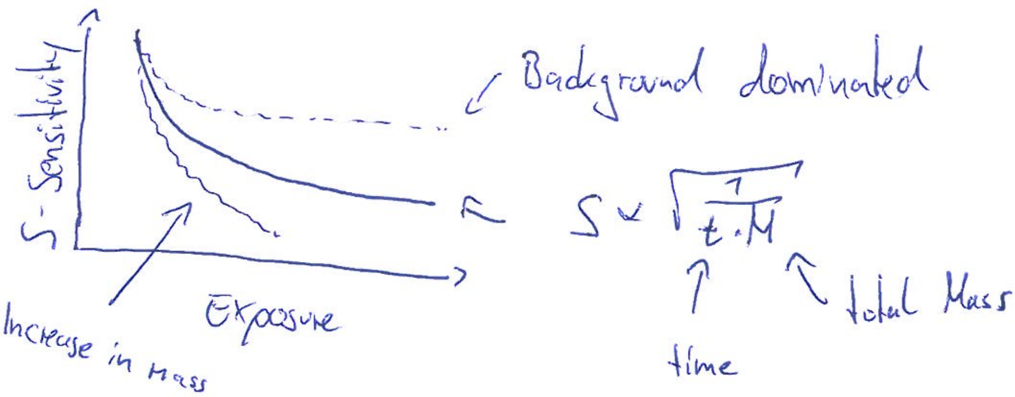
Rate equation – Spin independent:

$$\frac{dR}{dE} = \underbrace{\frac{\rho_0}{2\mu_A^2 m_\chi}}_{} \cdot F^2 \cdot \underbrace{\sigma_0}_{} \cdot A^2 \int_{v_{min}}^{v_{max}} \frac{f(v,t)}{v}\, dv$$

Parameters of DM!

with $v_{min} = \sqrt{\frac{m_A E_{thr}}{2\mu_A^2}}$

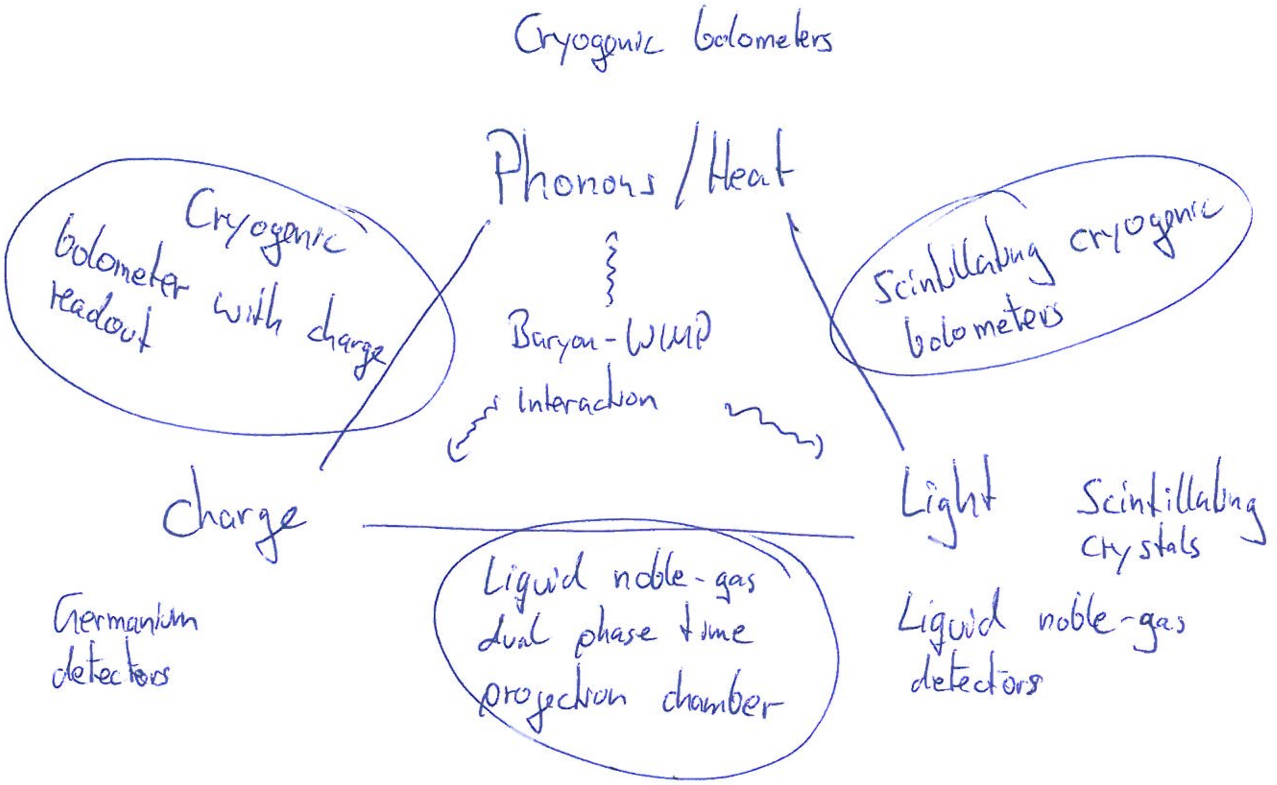
→ 



→ Detector:

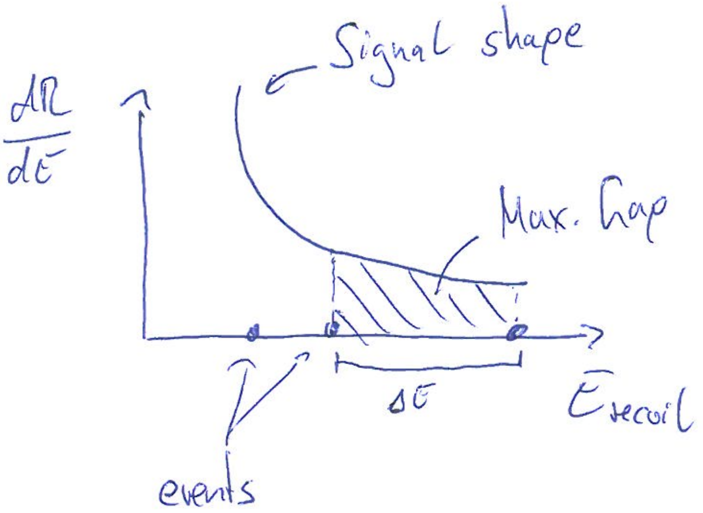
1. Small background – ~ 1 event per year
2. Large Mass ~ kg up to 1 ton
3. Low energy threshold ~ 1 keVnr
4. Duration of measurement ~ 1 year

Detector signals



◯ Allow for background discrimination!

More details: ArXiv: 1509.08767



$$x_i = \int_{E_i}^{E_{i+1}} \frac{dN}{dE}\, dE$$

expected number of events in gap

$$\Rightarrow C_0(x, \mu) = \sum_{k=0}^{m} \frac{(kx-\mu)^k e^{-kx}}{k!}\left(1 + \frac{k}{\mu - kx}\right)$$

observation given by data → gap sizes

expected number of total events → cross-section

→ find m so that $C_0 \to 0.9$ (Confidence level)

→ Only exclusion possible

→ very robust → no false signal claims

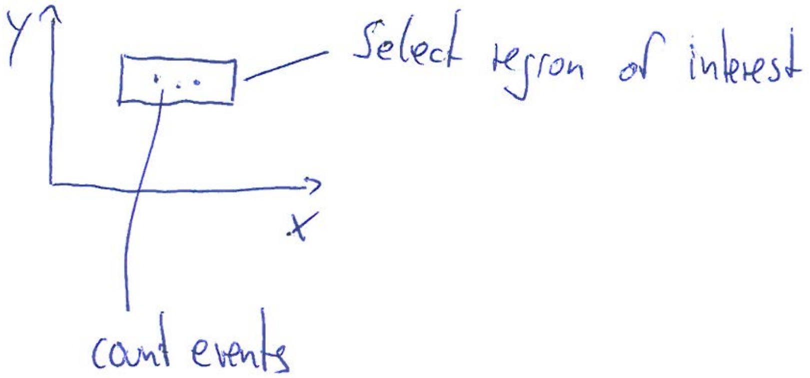
Profile Likelihood

$$\mathcal{L}(\sigma, \theta) = \prod_{i=1}^{N} \mathrm{Poiss}(N \mid N_b + N_s)\, \frac{N_s f_s + N_b f_b}{N_s + N_b}$$

$f_s = f_s(x_i)$
$f_b = f_b(x_i)$

Test statistic: $-q = 2\ln\left(\frac{\mathcal{L}(\sigma, \hat{\hat{\theta}})}{\mathcal{L}(\hat{\sigma}, \hat{\theta})}\right)$

② Statistics



→ **Feldman & Cousins:**

$$P(n|\mu) = (\mu+b)^n \frac{e^{-(\mu+b)}}{n!}$$

n : number of measured events

μ : signal

b : background expectation

→ You need/have a background prediction

→ FC gives method to avoid flip-flopping

– missing: • Error on b
• knowledge of shape in background or signal

→ **Maximum Gap**

- Use information about signal shape
- No information needed for background