

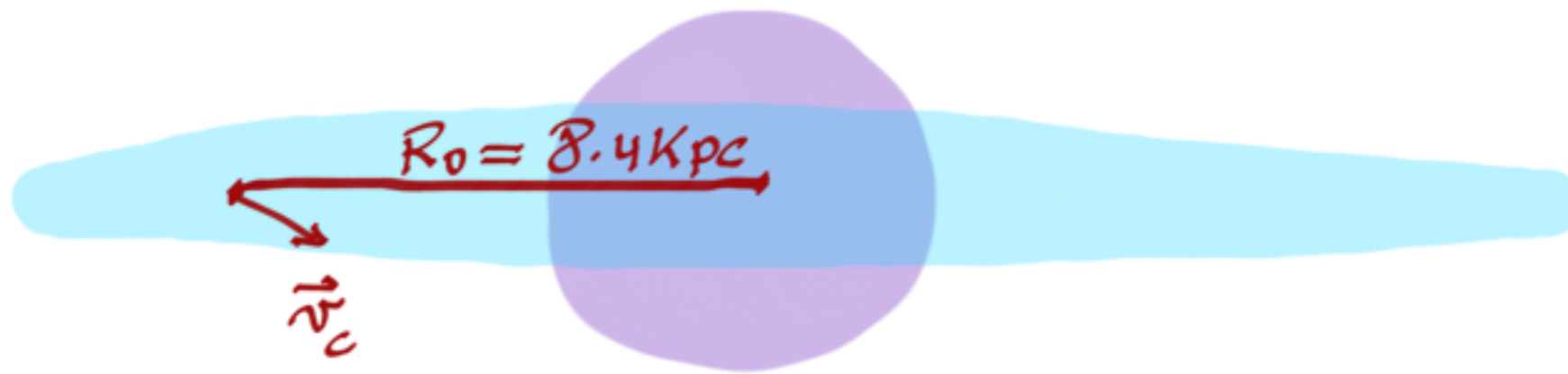
Light dark matter: new detection possibilities

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CERN, Sapienza University of Rome
and INFN Rome

OUTLINE

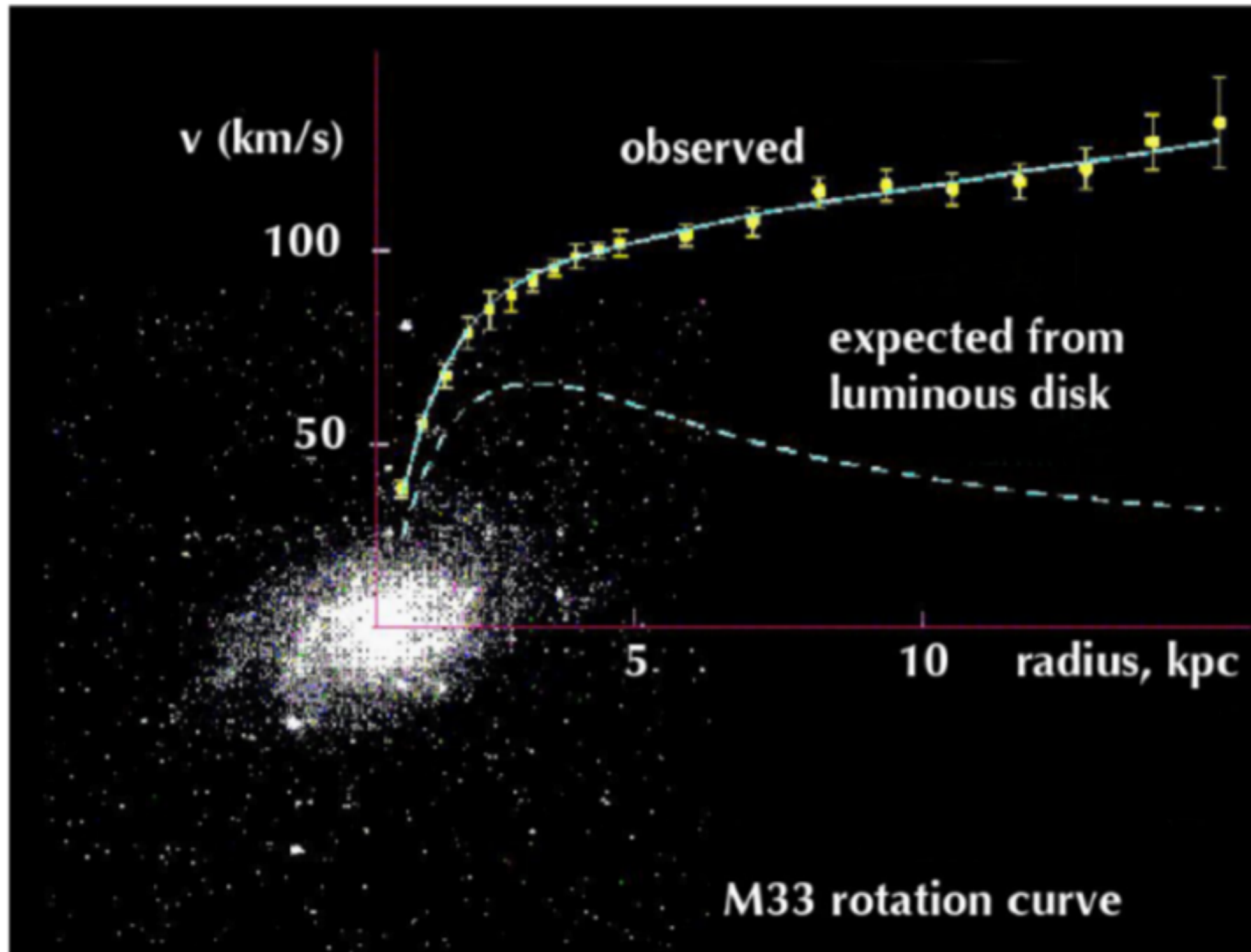
- I - DARK MATTER HALO AND NIMP WIND
- II - CARBON NANOTUBES AS DIRECTIONAL DETECTORS
- III - AXION-LIKE PARTICLES
- IV - LIGHT SHINING THROUGH WALL
WITH SUB-THz PHOTONS

DM halo



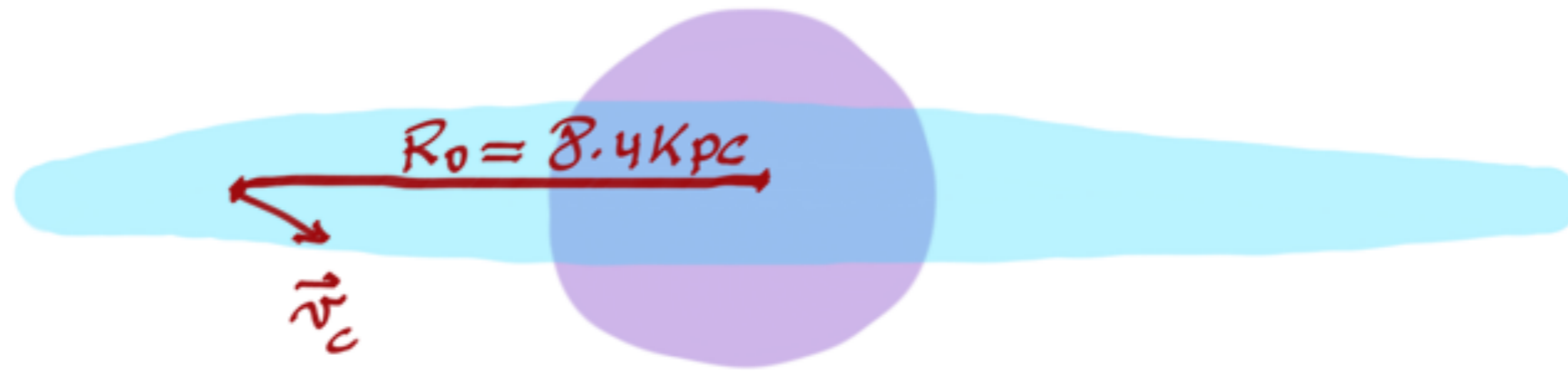
$$\frac{GM(r)}{r^2} = \frac{v_c^2(r)}{r}$$

(Velocity of the local Standard of Rest)



FROM HI ABSORPTION LINES (neutral atomic Hydrogen cloud in interstellar medium)

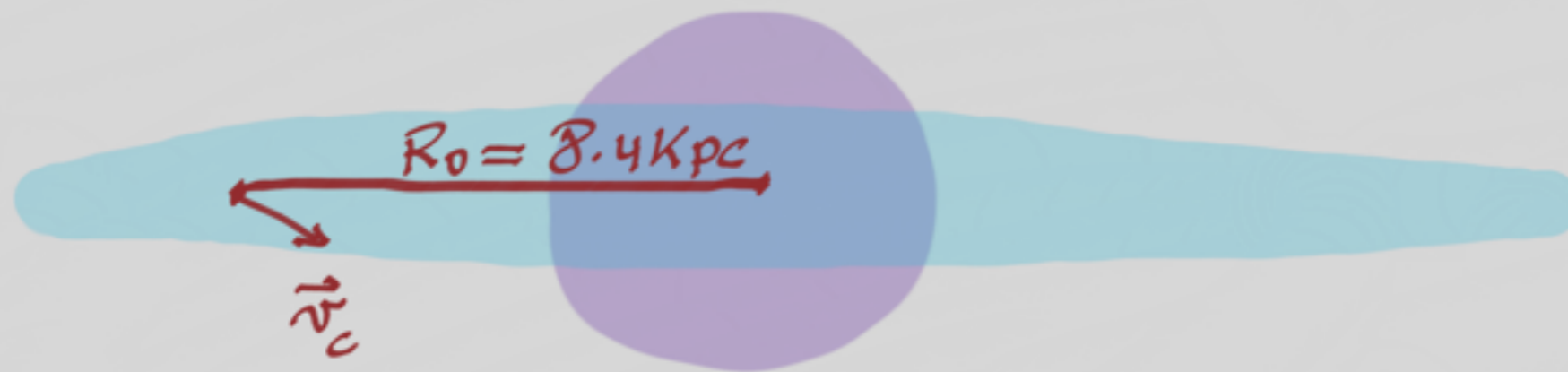
DM halo



$$\frac{GM(r)}{r^2} = \frac{v_c^2(r)}{r} \Rightarrow \rho_{DM} \sim \frac{1}{r^2}$$

out of the edge of the luminous disk

DM halo



$$M_{\text{DM}}(R_0) = \frac{v_c^2 R_0}{G} - \underbrace{M_{\text{DISK}}}_{M_{\text{W MAX}} \approx 6 \times 10^{10} M_{\odot}}$$

$$\vec{v}_c = (0, 235, 0) \text{ km/s}$$

$$M_{\text{DM}}(R_0) \approx \frac{1}{2} M_{\text{DISK}}$$

DM halo

Any function f of the energy alone $f(E)$ is an equilibrium distribution ($\partial f / \partial t = 0$) of a collisionless Boltzmann eq. ($df/dt = 0$ or $C[f] = 0$).

$$f(\vec{v}) = \left(\frac{1}{\pi v_0^2} \right)^{3/2} e^{-\vec{v}^2/v_0^2} \quad (\text{Galaxy frame})$$

$$v_0 \sim v_{c, \infty} \approx 235 \text{ km/s}$$

Considering that particles with $v > v_{\text{esc}}(r)$ will not be gravitationally bound to the MW.

$$v_{\text{esc}} = \sqrt{2 |\Phi(r)|}$$

$$v_{\text{esc}}^2 = 2v_c^2 + \frac{8\pi G}{3} \int_{R_0}^{\infty} \rho(r) r dr$$

v_{esc} contains info. on the mass outside the solar circle.
The fact that $v_{\text{esc}} \gg \sqrt{2} v_c$ indicates significant amount of mass exterior to solar circle.

$$v_{\text{esc}} \approx 498 \div 608 \text{ km/s}$$

(from "high velocity stars")

DM halo

$$f(\vec{r}) = \begin{cases} \frac{1}{N} \left(\frac{1}{\pi v_0^2} \right)^{3/2} \left[e^{-\frac{v^2}{v_0^2}} - e^{-\frac{v_{esc}^2}{v_0^2}} \right] & (v < v_{esc}) \\ 0 & (\text{otherwise}) \end{cases}$$

- * The assumption of a smooth halo might not be so good - Halo substructure may affect directionality.
- * A co-rotational DM disk might exist, $\rho \sim 10 \div 50\%$ of ρ_{loc}^{DM} ($= 5 \cdot 10^{-25} \text{ gr/cm}^3$)

Left-over particles

In absence of annihilations

$$n(t) a^3(t) = n(t_0) a^3(t_0)$$

let σ be the xx exothermic annihilation x sect.

$$n(t) a^3(t) = \frac{n(t_0) a^3(t_0)}{1 + n(t_0) a^3(t_0) \int_{t_0}^t \frac{\langle v \sigma \rangle}{a^3(t')} dt'}$$

$t \rightarrow +\infty$

where $[p v \sigma] = \kappa \Gamma^{-1}$

If the integral in the denominator is too large, there are no left-over particles.

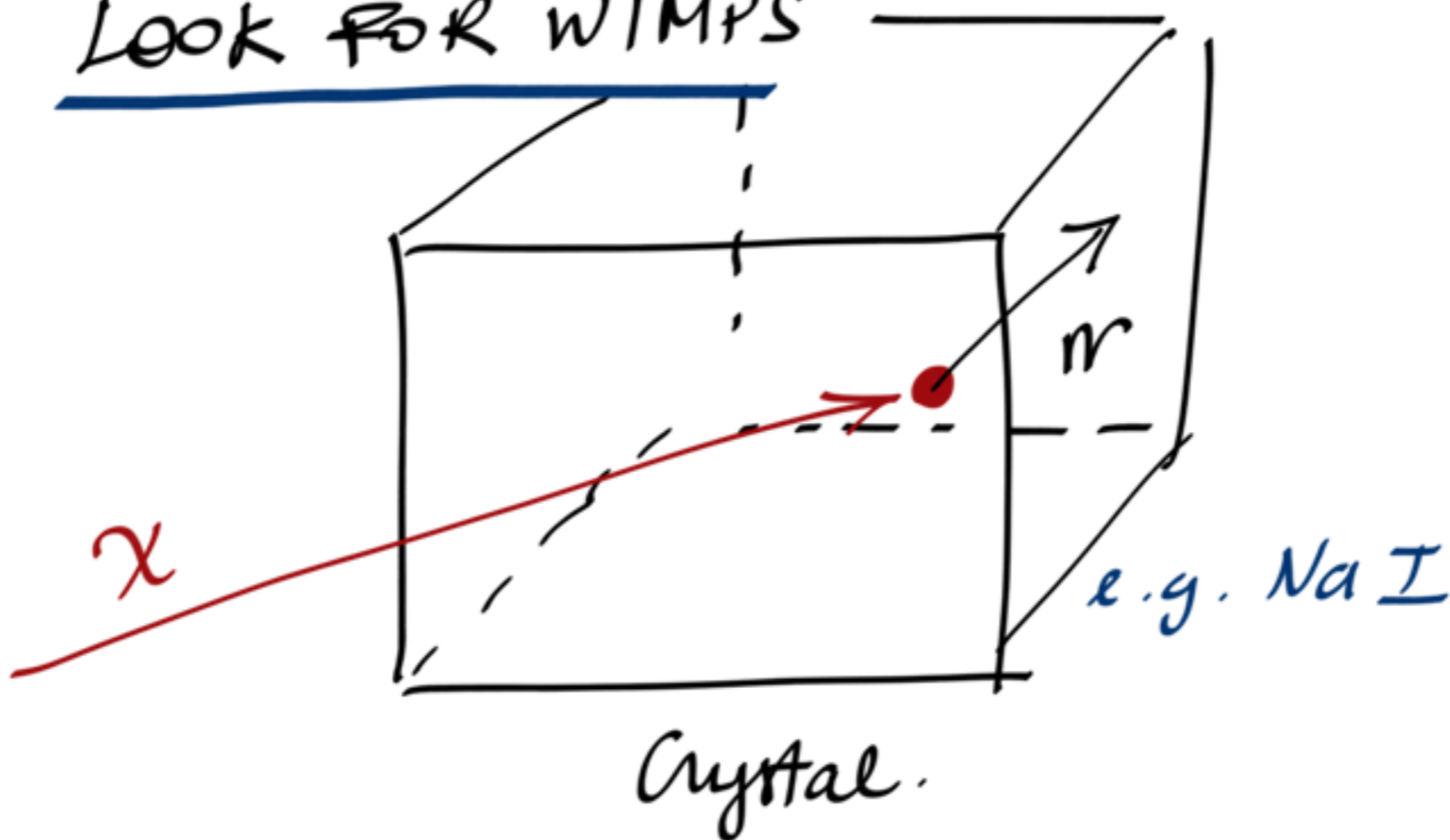
$$(\langle v \sigma \rangle \sim \kappa \frac{k^{2L+1} k'^{2L+1}}{k^2} \text{ \& \ } k \rightarrow 0, k' \rightarrow \text{const.}; T \sim a^{-1}; a \sim t^{2/3}; \langle \cdot \rangle_{\text{av}} \sim \int dE e^{-E/T} \dots)$$

WIMPS

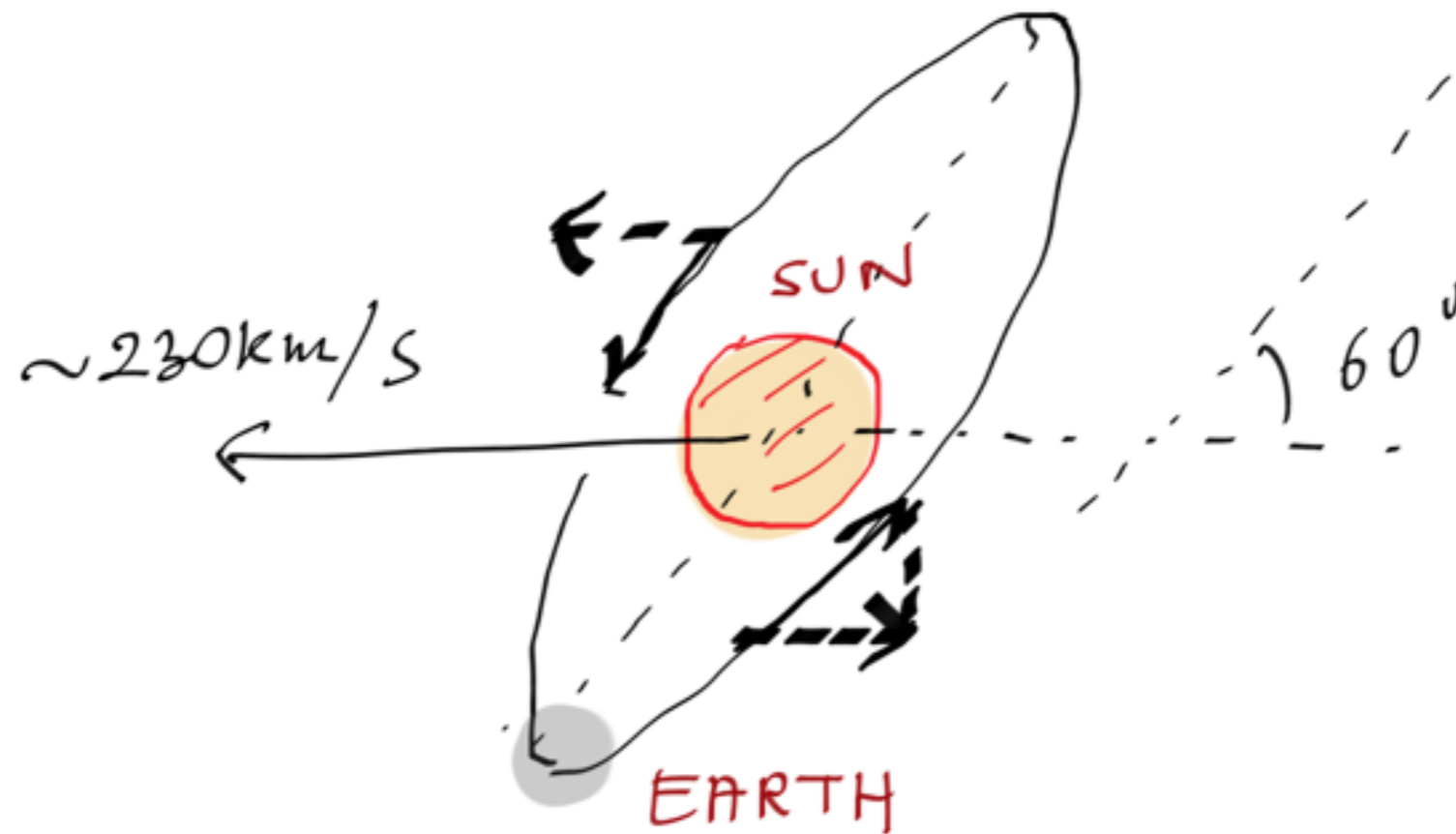
χ of $M_\chi \approx 100$ GeV weakly inter.
with $\langle \sigma v \rangle \approx 10^{-26} \text{ cm}^3/\text{sec}$ give
a LEFT OVER Ω WHICH IS

$$\Omega \approx \Omega_{\text{DM}}$$

LOOK FOR WIMPS



WIMP WIND



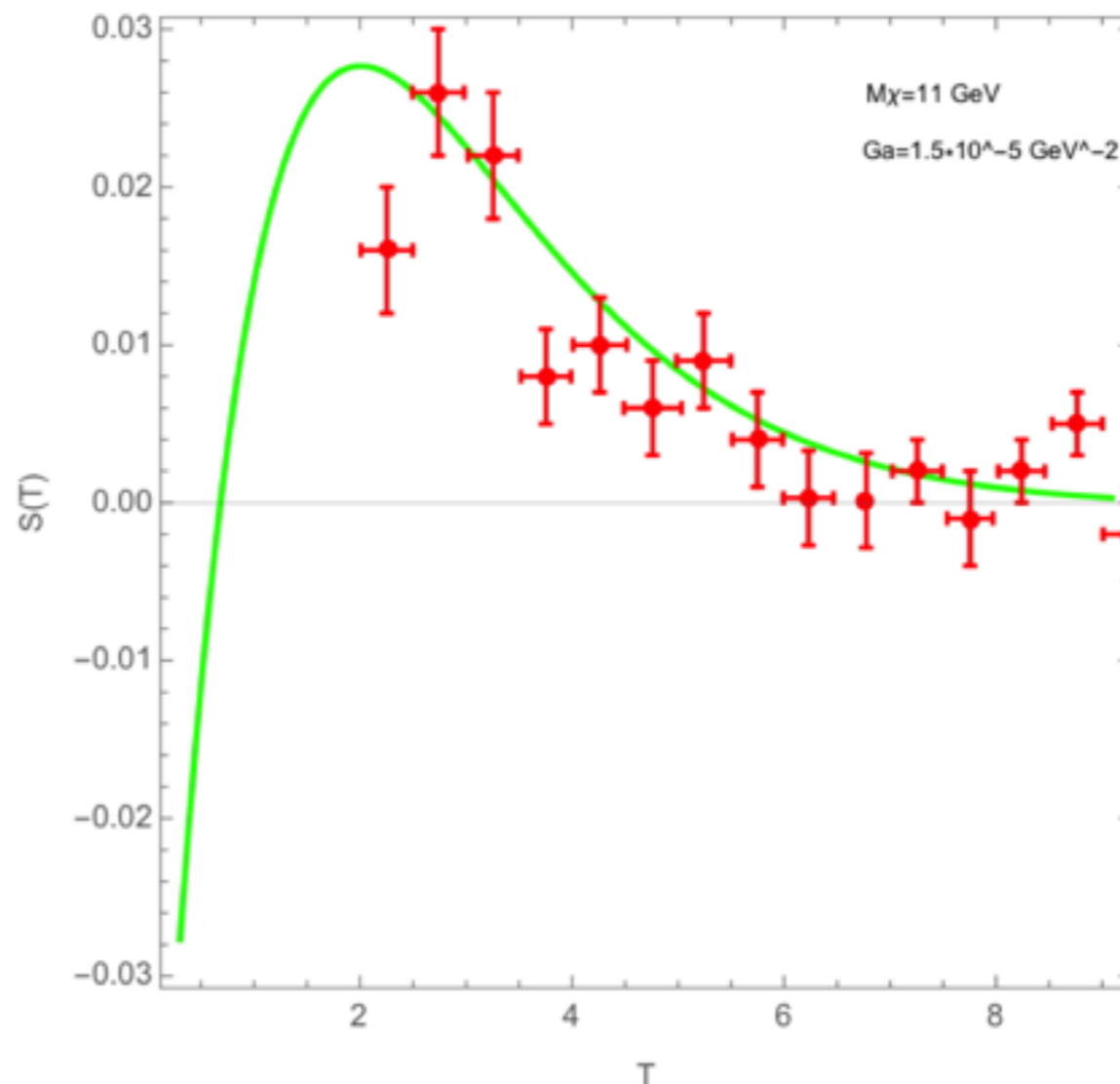
$$\vec{w}(t) = [232 + 15 \cos \psi(t)] \hat{k}$$

$$\psi(t) = 2\pi \frac{t - 152.5}{365.25} = \omega t + \varphi_0$$

DAMA

$$\frac{d\Gamma}{dT} = A(T) + S(T) \cos(\omega t + \varphi_0)$$

$$\left(\frac{\text{cpd}}{\text{kg KeV}} \right)$$

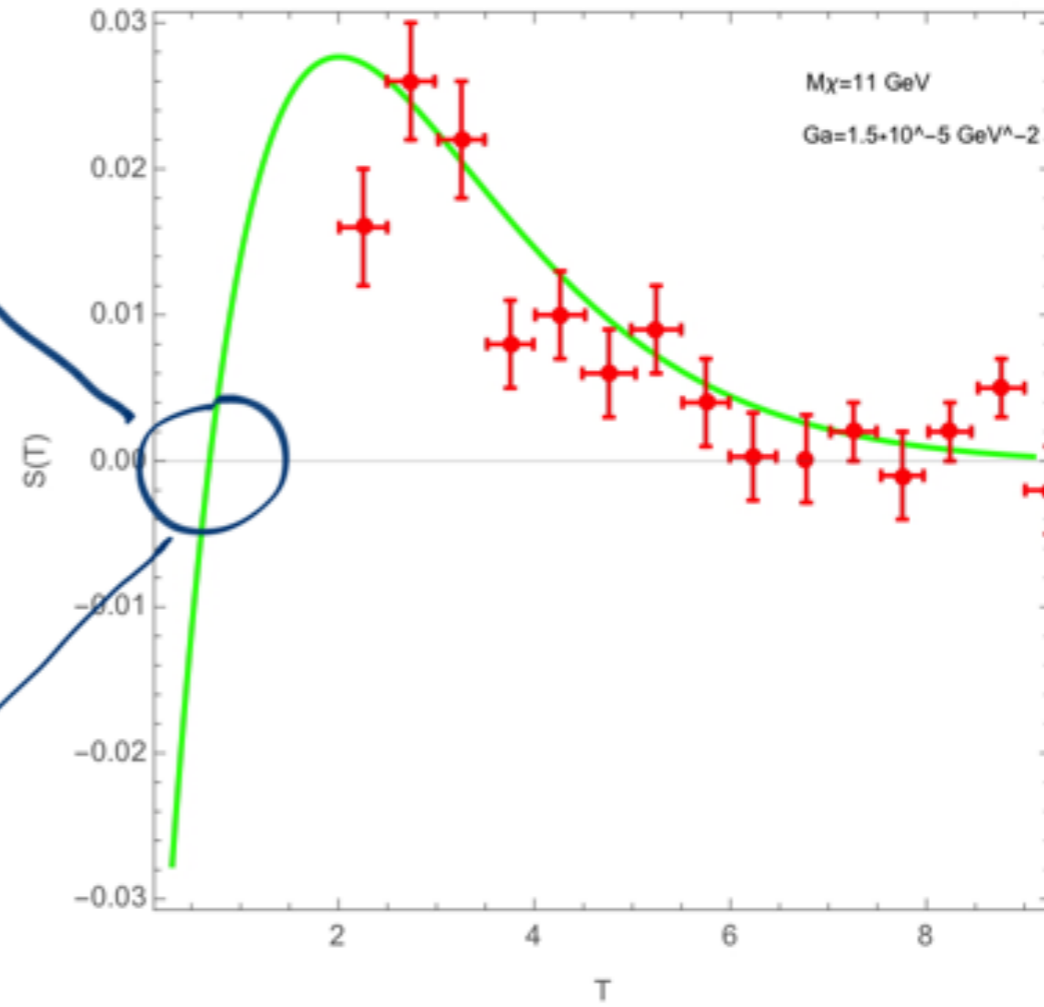
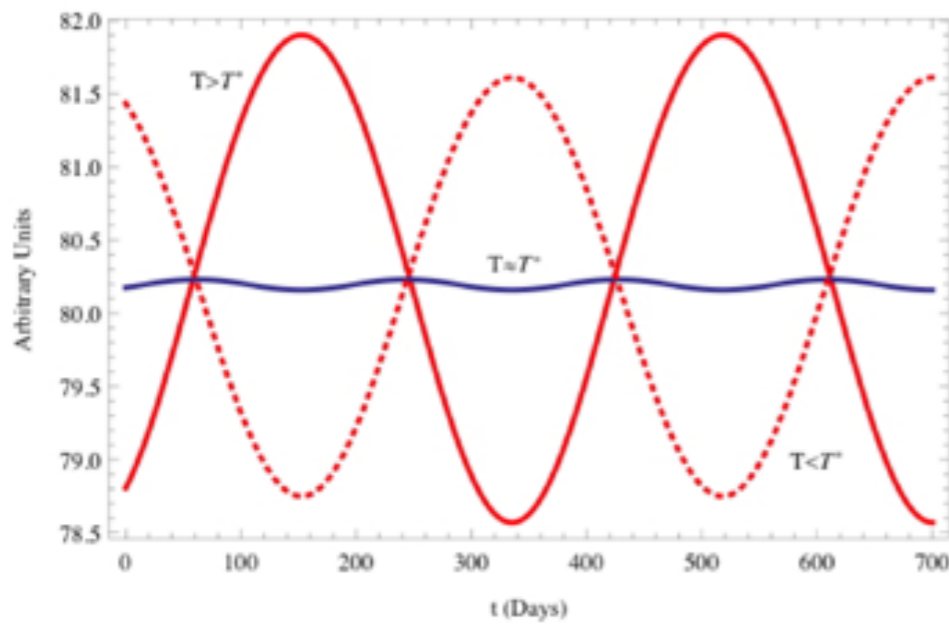


χ -Na
in NaI

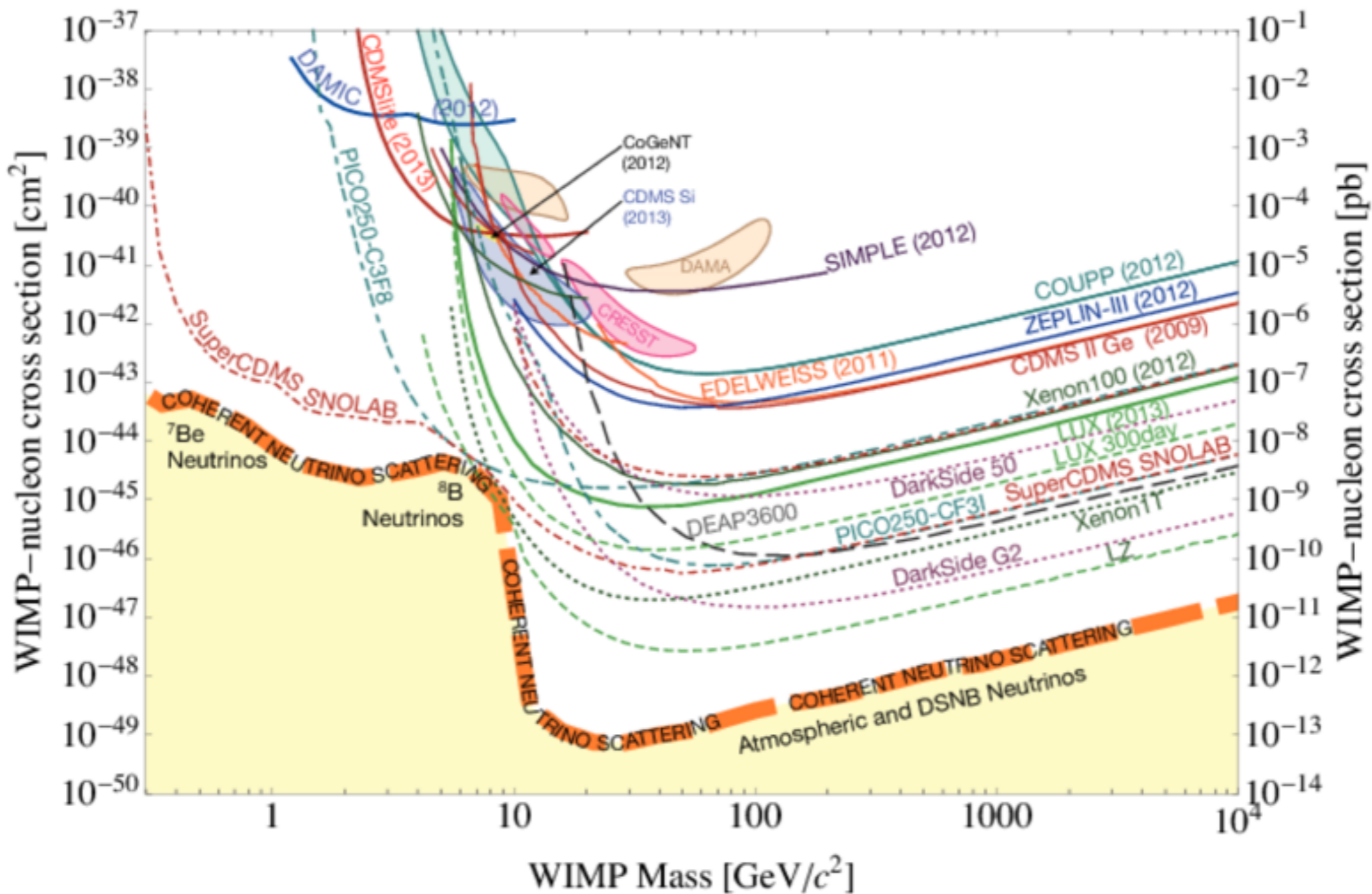
NUCLEAR RECOIL KINETIC ENERGY
(KeVee)

DAMA

$$\frac{dR}{dT} = A(T) + S(T) \cos(\omega t + \varphi_0)$$

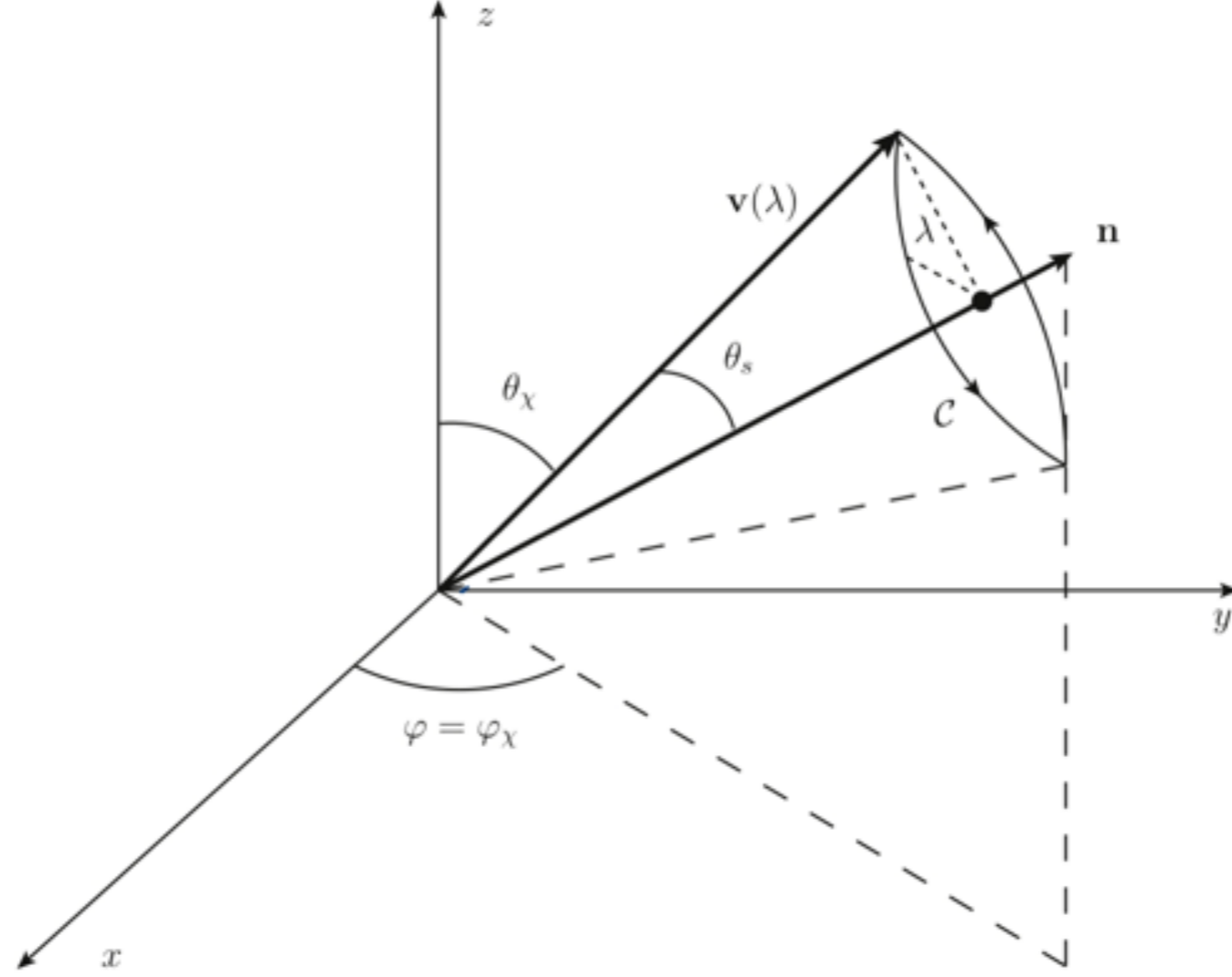


EXCLUSION PLOT



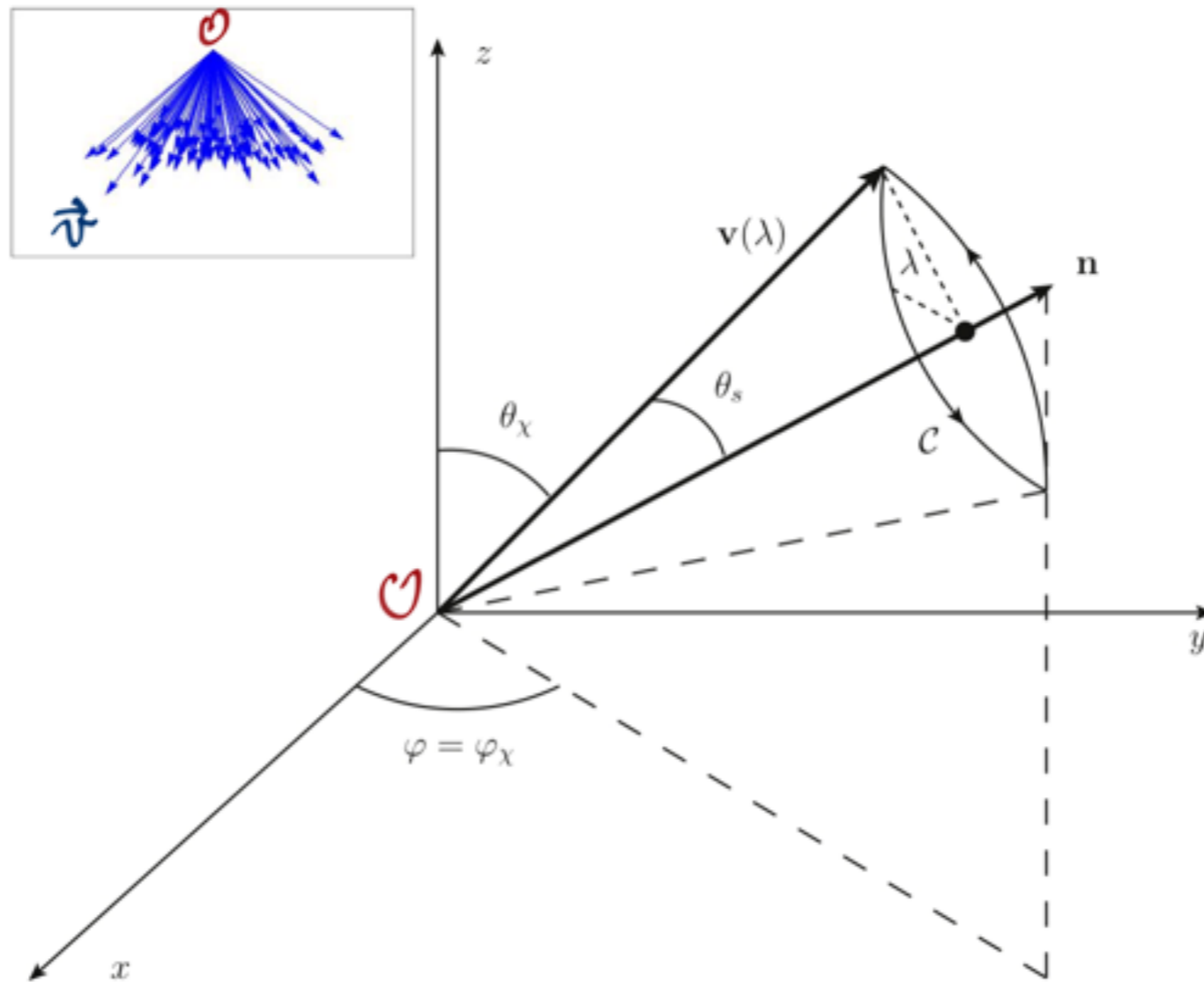
WIMP WIND

★ CYGNUS



WIMP WIND

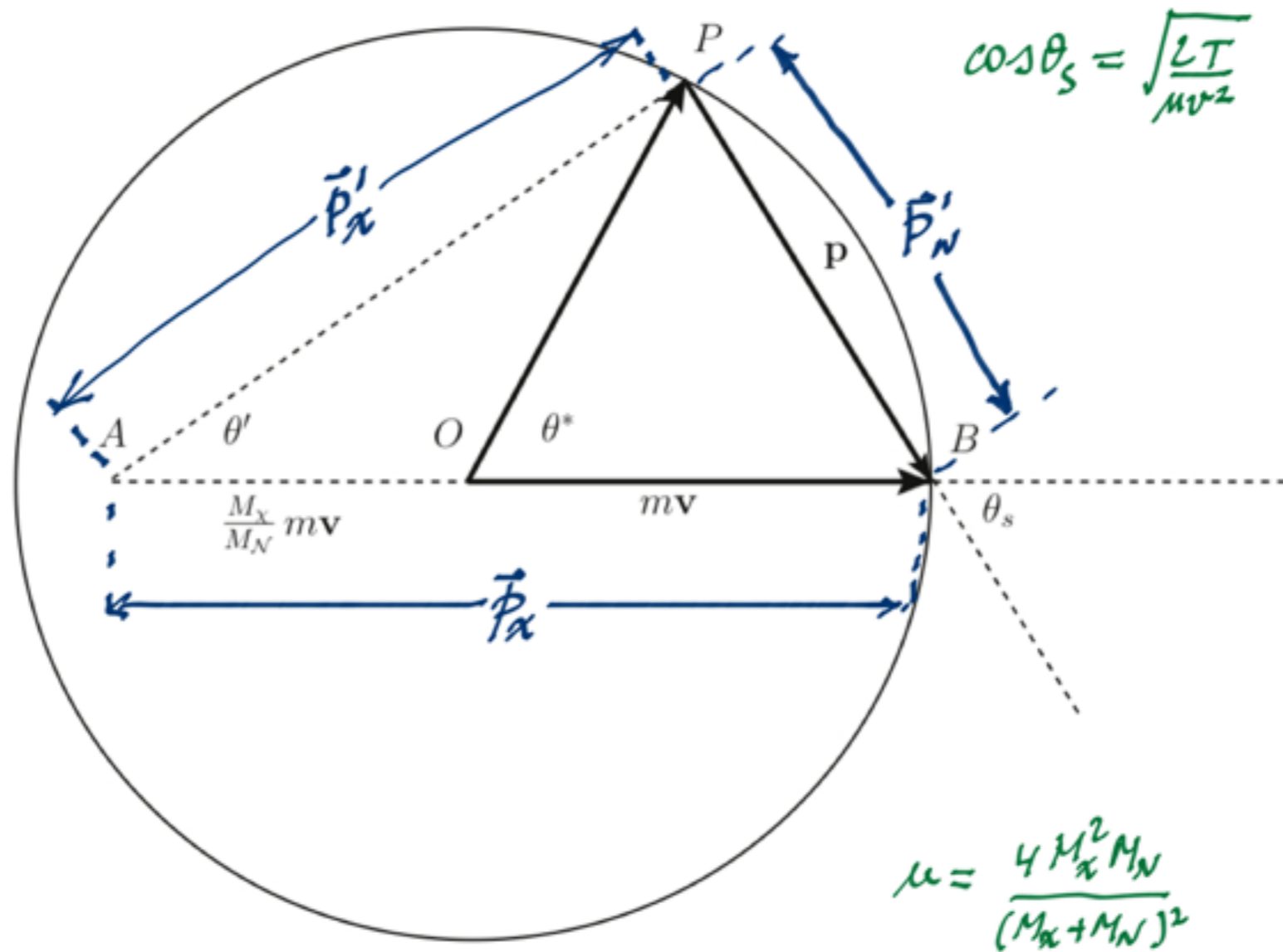
★ CYGNUS



$$f(\vec{v}) = \beta e^{-\alpha (\vec{v} + \vec{w}(t))^2}$$

$\theta (\equiv \theta_x + \theta_s \text{ if } \lambda=0) \approx \pi$ is the wind orientation

Kinematics



$$\frac{(\overline{T'_N})_{\max}}{T_x} = \frac{4x}{(1+x)^2}, \quad x = \frac{M_x}{M_N}, \quad \text{Graph of } \frac{(\overline{T'_N})_{\max}}{T_x} \text{ vs } x$$

Nucleon Recoils

$$\frac{d\Gamma}{d\Omega_n} = n_\chi \langle v \frac{d\sigma}{d\Omega_n} \rangle_{\vec{v}}$$

As a working point we take DAMA data on WIMP- Na collisions

$$\sigma_{\chi p} \approx 2 \cdot 10^{-4} \text{ pb}$$

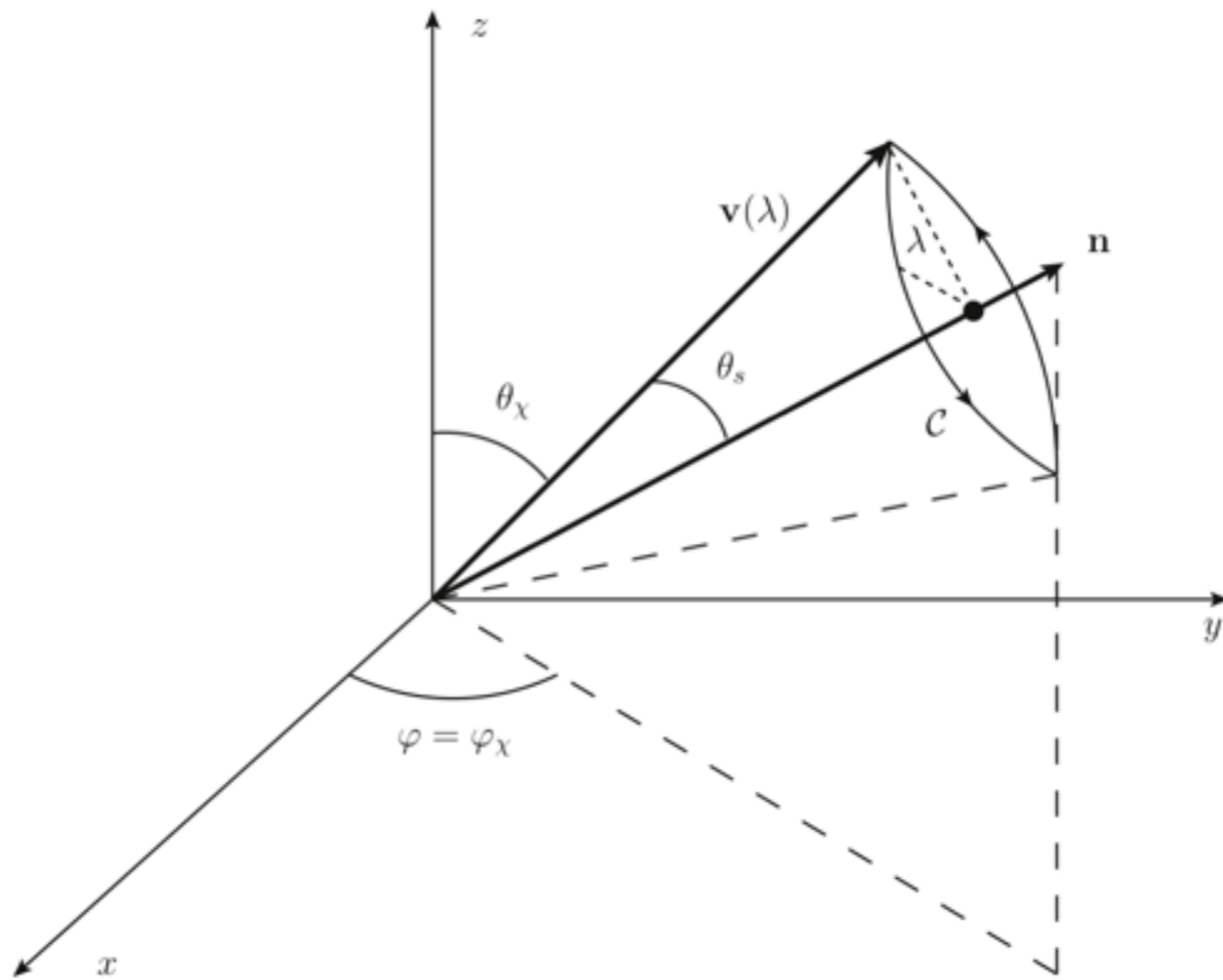
With this we find

$$G_A = \frac{A^2}{4} G \approx 10^{-5} \text{ GeV}^{-2}$$

with $A=12$ and $M_\chi \approx M_c$

WIMP WIND

★ CYGNUS



WIMP WIND

$$\vec{v}(\lambda, \theta_s) = \vec{v}_0 \cos \lambda + \underbrace{\hat{n} (\hat{n} \cdot \vec{v}_0)}_{\sim \cos \theta_s} (1 - \cos \lambda) + \underbrace{(\vec{v}_0 \times \hat{n})}_{\sim \sin \theta_s} \sin \lambda$$

Since $d\sigma/d\Omega_{\vec{n}}$ is isotropic, $\langle v d\sigma/d\Omega_{\vec{n}} \rangle_{\vec{n}} \sim$

$$\int d^3v f(\vec{v}(\lambda, \theta_s)) = \int d^3v f(\vec{v}(\lambda, \theta_s)) \int dT \delta(T - \frac{1}{2} \mu v^2 \cos^2 \theta_s)$$

$$\mu = \frac{4 M_\chi^2 M_N}{(M_\chi + M_N)^2}$$

$$= \int dT \int dv v^2 \int d\lambda \int d\cos \theta_s f(\vec{v}(\lambda, \theta_s)) \delta(T - \frac{1}{2} \mu v^2 \cos^2 \theta_s)$$

$$= \int dT \int dv v^2 \int d\lambda f(\vec{v}(\lambda)) \frac{1}{v \sqrt{2\mu T}}$$

$$\frac{d\Gamma}{dT d\cos \theta} = C \int_{\frac{v_{\text{esc}}}{\sqrt{2\mu T}}}^{v_{\text{esc}}} dv \cdot v \int_0^{2\pi} d\varphi \int_0^{2\pi} d\lambda f(\vec{v}(\lambda))$$

$$\text{use } \int_0^{2\pi} d\lambda e^{-\alpha(A+B\cos\lambda)} = 2\pi e^{-\alpha A} I_0(\alpha B)$$

WIMP WIND

$$\frac{d\Gamma}{dT d\cos\theta} = C \int_{\sqrt{2T/\mu}}^{v_{\text{esc}}} dv v^\beta e^{-\alpha A} I_0(\alpha B)$$

$$A = v^2 + w^2(t) + 2vw_z(t) \cos\theta_s \cos\theta$$

$$B = 2vw_z(t) \sin\theta_s \sin\theta$$

$$C = K \frac{m_\chi G_A^2 \Lambda^4 F_A^2(2M_N T)}{16 M_\chi^2 M_N}$$

$$\Lambda \sim \sqrt{s} \simeq M_\chi + M_N$$

$$K = 5 \cdot 10^7$$

to get $\frac{\text{cpd}}{\text{kg KeV}}$ for CNTs

velocities v in units of c

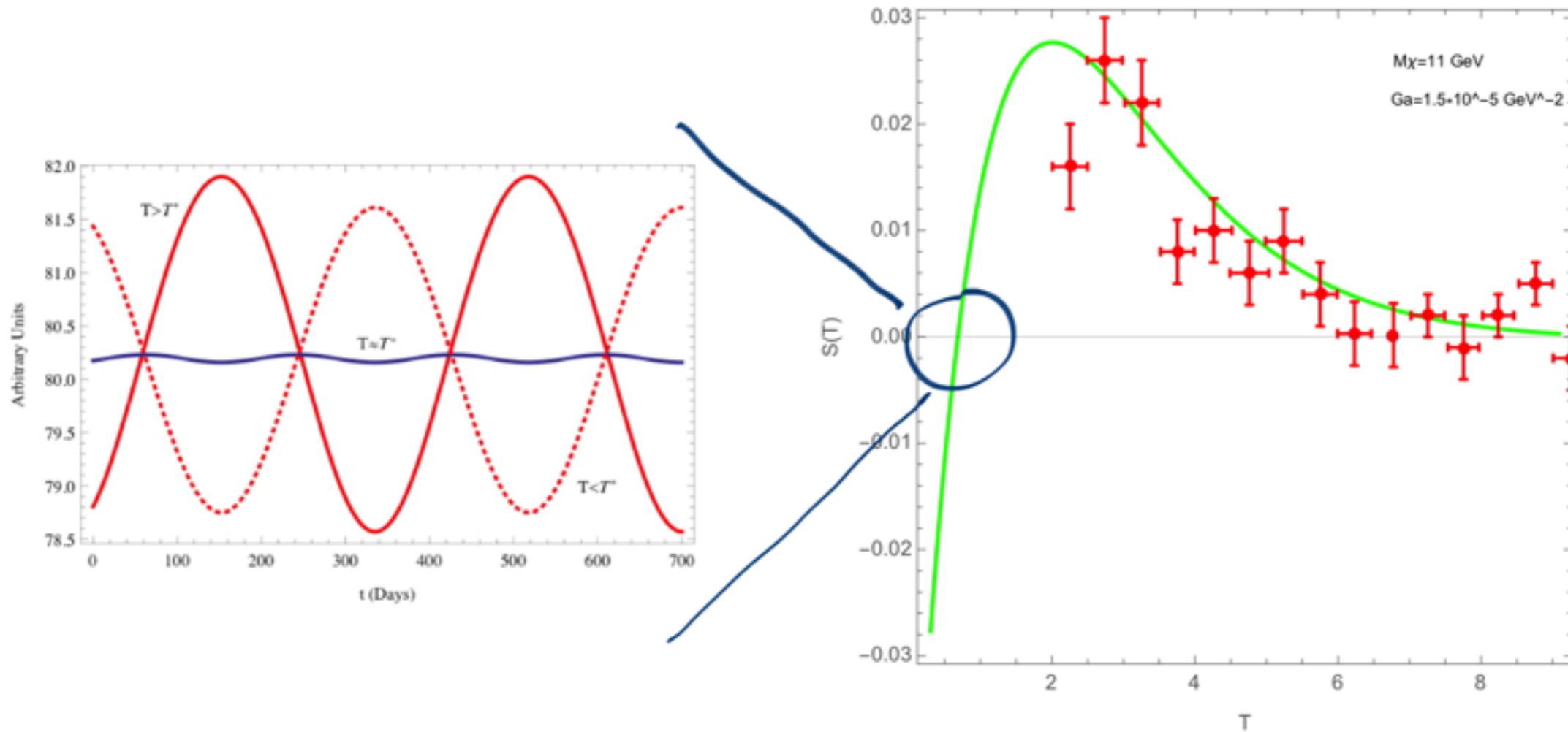
$$v_{\text{esc}}(\text{on } \oplus) \simeq 780 \text{ km/s}$$

$$m_\chi = \rho_\chi / M_\chi = 0.4 \text{ GeV/cm}^3 / 11 \text{ GeV}$$

$$G_A \simeq 10^{-5} \text{ GeV}^{-2}$$

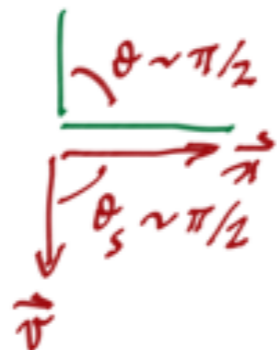
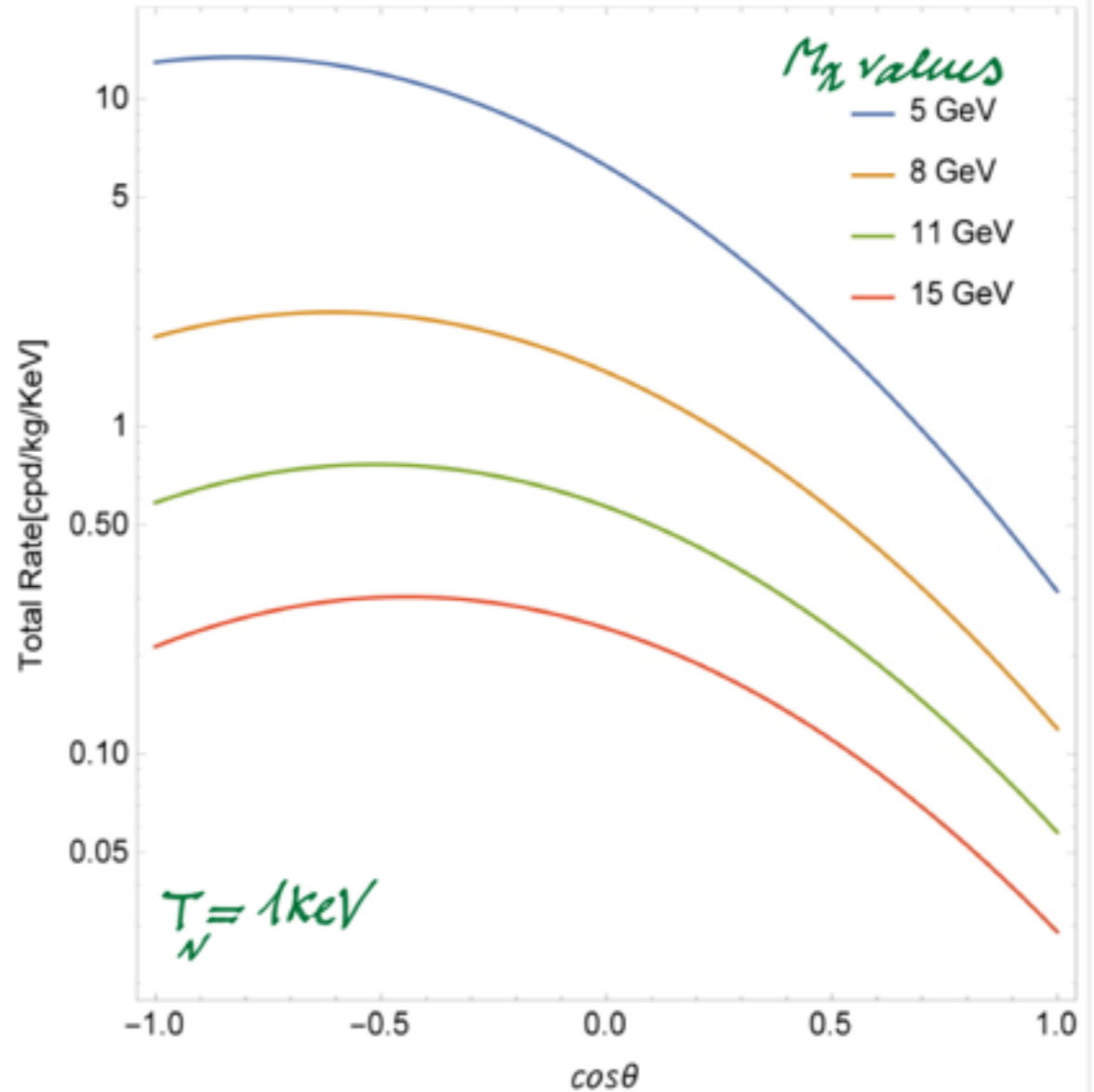
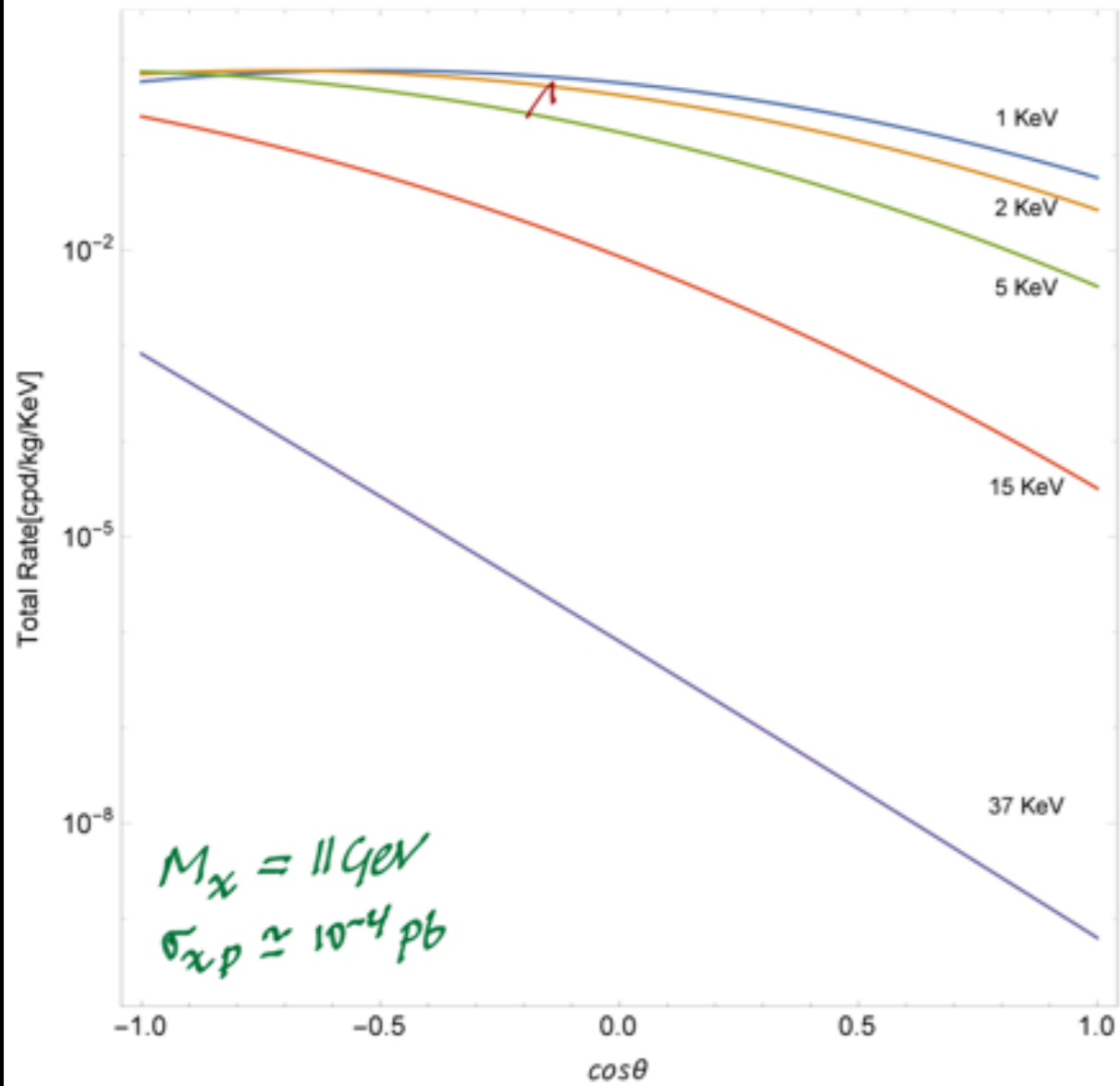
DAMA

$$\frac{d\Gamma}{dT} = A(T) + S(T) \cos(\omega t + \varphi_0)$$



$$\frac{d\Gamma}{dT} = \int d\cos\theta \frac{d\Gamma}{dT d\cos\theta} \rightarrow \text{Fermi exp.}$$

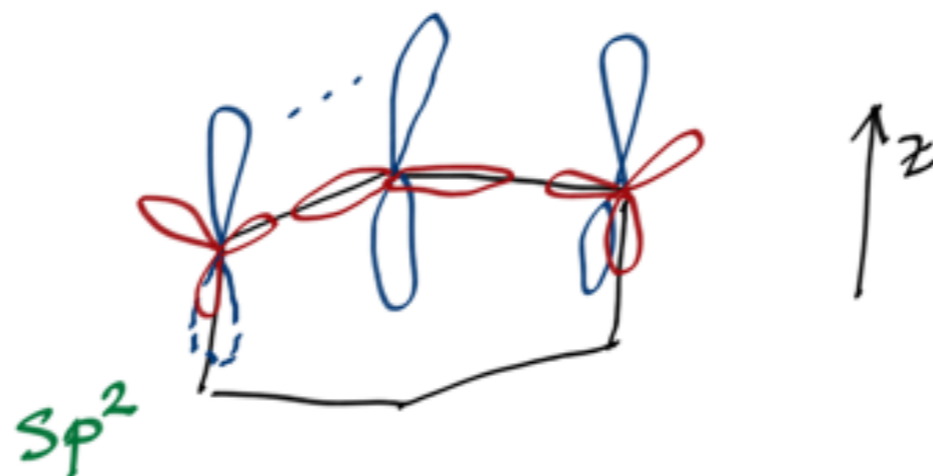
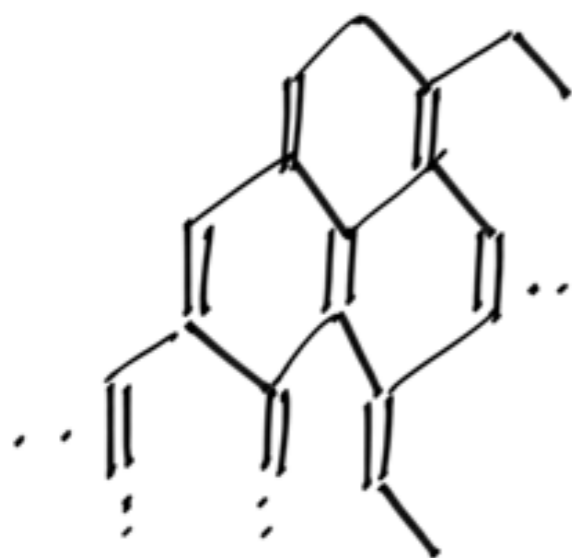
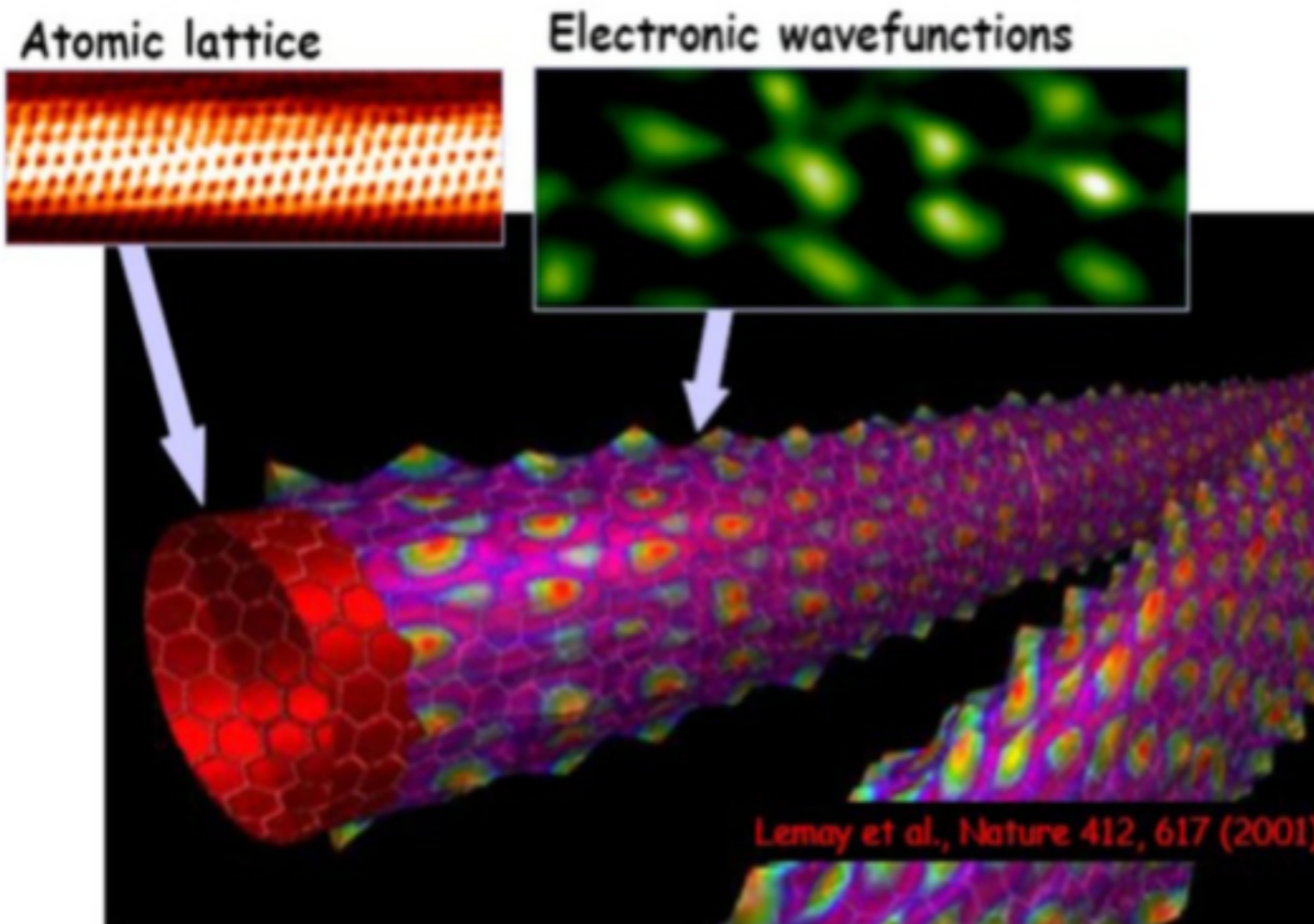
Nucleon Recoils



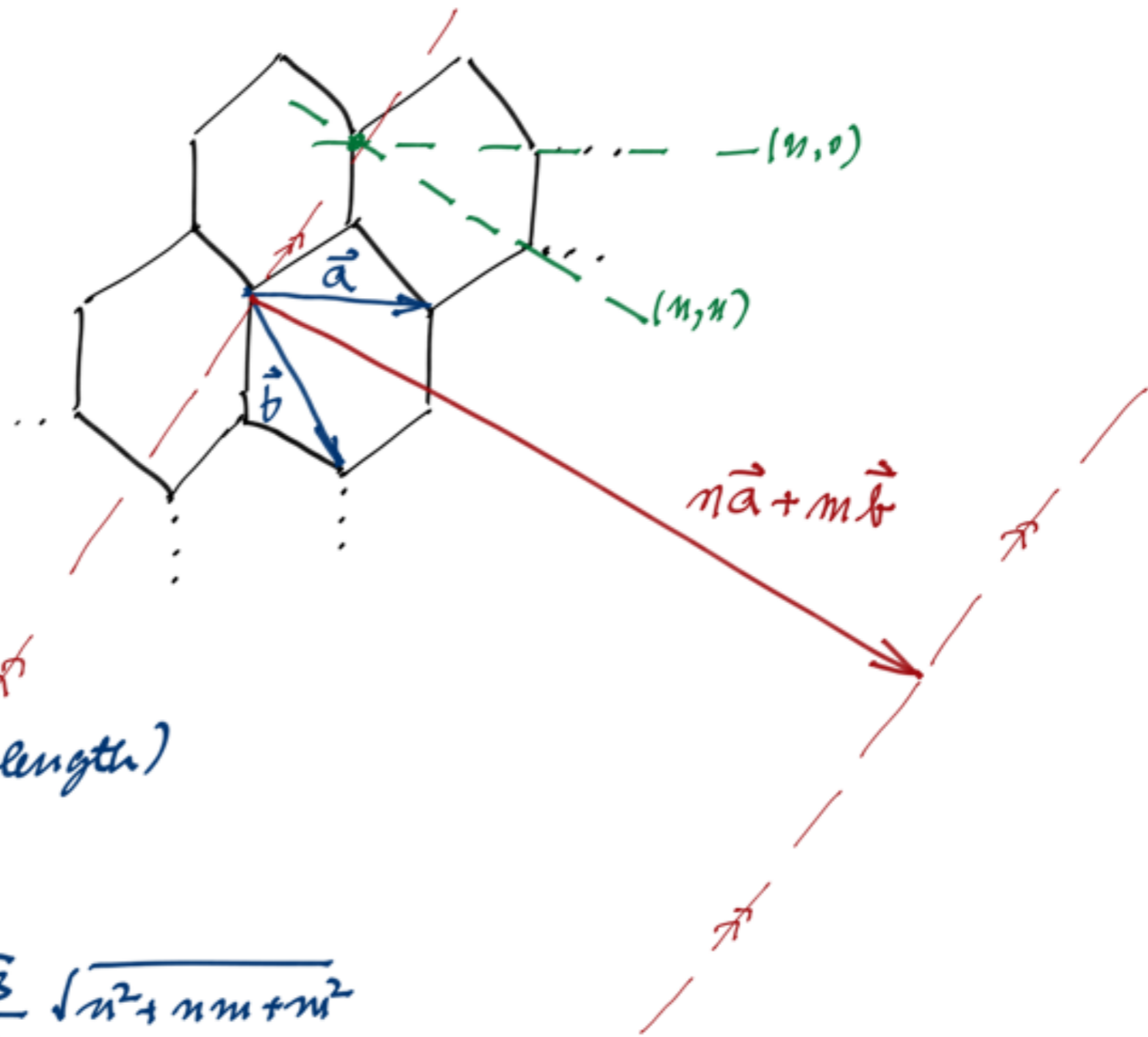
If T is increased, more countings with heavier WIMPs.

$$T_N^{\text{max}} \underset{x \rightarrow 1}{\sim} T_\alpha$$

CNT Target



CNT Target



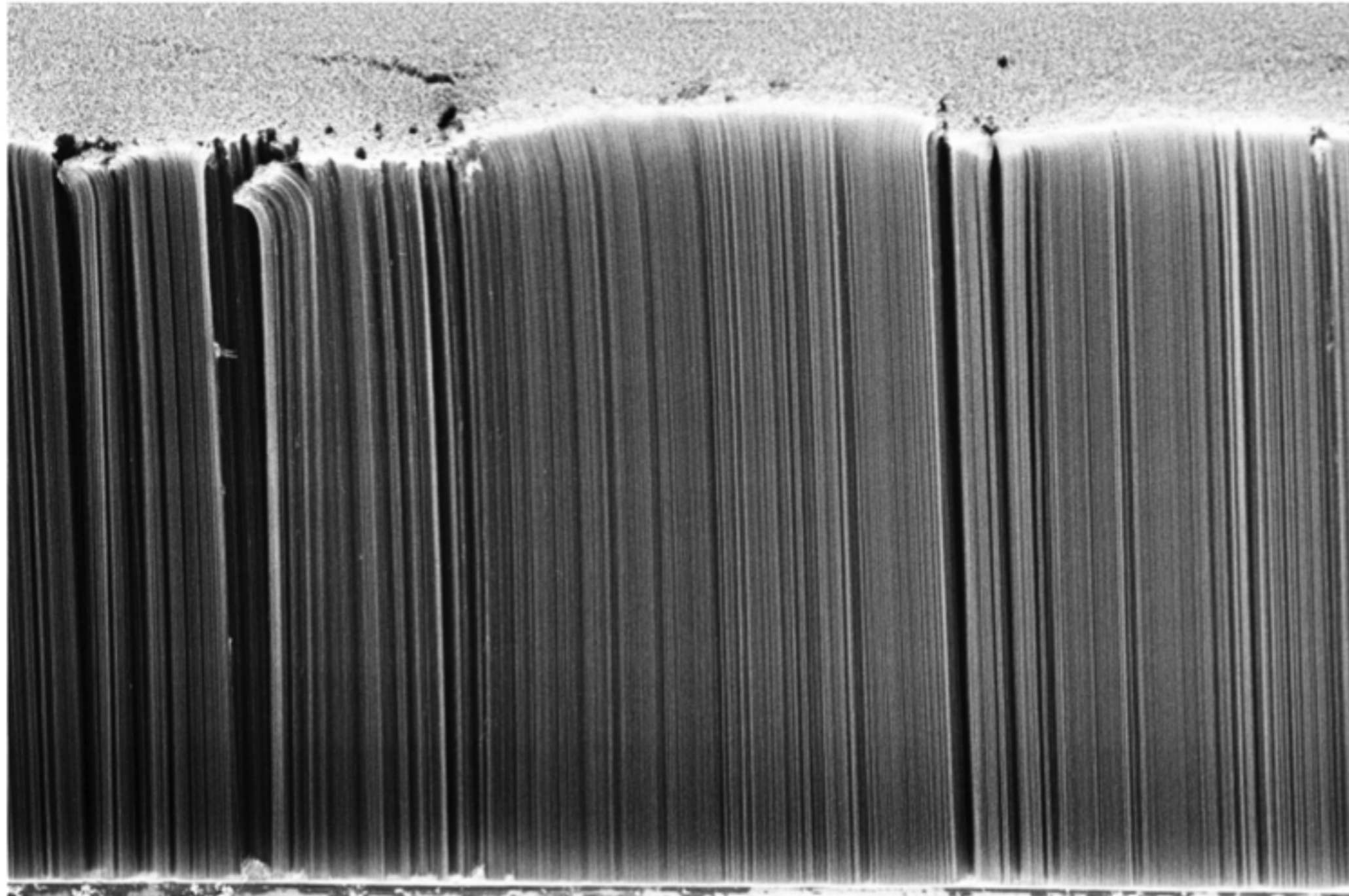
$l \approx 0.14 \text{ nm}$ (bond length)

$$|\vec{a}| = |\vec{b}| = l\sqrt{3}$$

$$R_{CNT} = \frac{l\sqrt{3}}{2\pi} \sqrt{n^2 + nm + m^2}$$

- (n, n) "ARMCHAIR" - METALLIC
- (n, m) with $(n-m)$ multiple of 3 - SEMICONDUCT.
- $(n, 0)$ "ZIG-ZAG"

CNTs



20 μ m
|-----|

EHT = 8.00 kV
WD = 7.0 mm

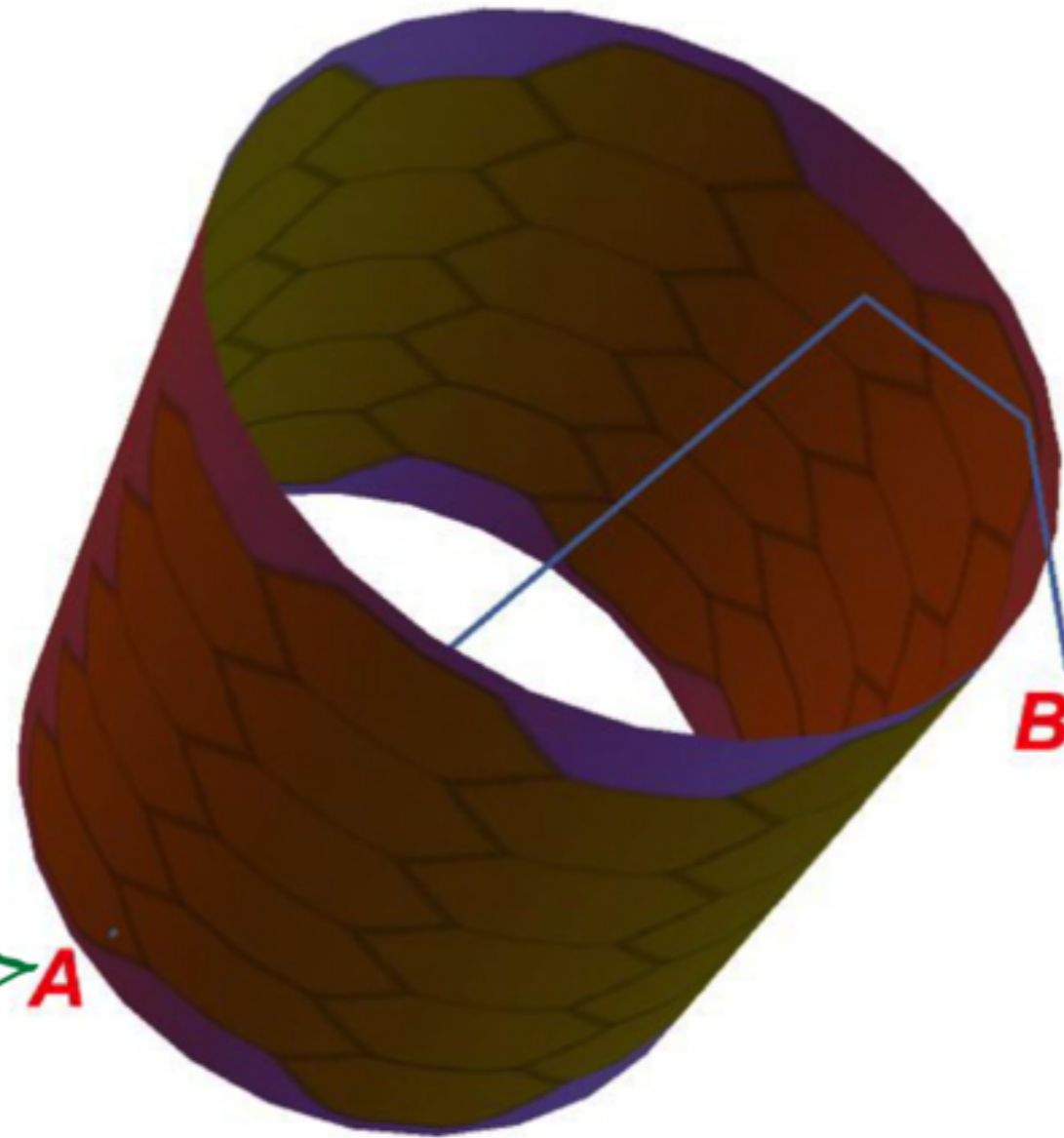
Signal A = InLens
Mag = 800 X

Date :28 May 2015
Sample ID =

CNIS

CNT Target

A: $\sigma_I \sim \frac{|J_{in} \alpha|}{k}$
($1/v$ law)



B: $\sigma_{\pm} \sim \frac{1}{k^2} e^{-2\pi/k}$
 $\exp(-2\pi Z_1 Z_2 \frac{\alpha}{v})$

(T, θ) with $M_x = 11 \text{ GeV}$.

GENERATE AN ARRAY OF (T, θ) FROM $d\Gamma/dT d\cos\theta$

Extraction of a C ion

$C=C$ 145 kcal/mol

$C-C$ 85 kcal/mol

The extraction price of one C atom $\lesssim 20$ eV

The ionization $C \rightarrow C^{4+}$ costs ~ 147 eV

C^{5+} " ~ 539 eV

C^{6+} " ~ 1029 eV

M_π (GeV)	T (keV)	T_N^{\max} (keV)
50	[25, 177]	[15, 109]
100	[50, 354]	[20, 135]
⋮		

CNT POTENTIALS

Effective potential in the transverse plane

$$U(r, \varphi) = U_0(r) + 2 \sum_{s=1}^{\infty} U_{sN}(r) \cos\left(\frac{\pi s(n+m)}{q}\right) \cos\left(sN\varphi + \frac{\pi s(n-m)}{q}\right)$$

$$= \sum_{\text{chains}} \bar{U}\left(\begin{array}{c} \vdots \\ \vdots \\ \vdots \end{array}\right) \quad - \text{each } \bar{U} \text{ as a Fourier series of azimuthal harmonics}$$

$$q = \text{gcd}(2m+n, 2n+m)$$

$$N = \frac{2}{q} (n^2 + mn + m^2) \quad \#/2 \text{ of rows parallel to the axis}$$

$$U_v(r) = 4\sqrt{\pi} \sigma \underbrace{z^2}_{\wedge} e^2 \left(\frac{R}{r}\right)^{1/2} \sum_{j=1}^4 a_j b_j e^{-b_j^2 (r^2 + R^2)} \times e^{2b_j^2 rR \left[\sqrt{1+\xi^2} - \xi \ln(\xi + \sqrt{1+\xi^2}) \right]}$$

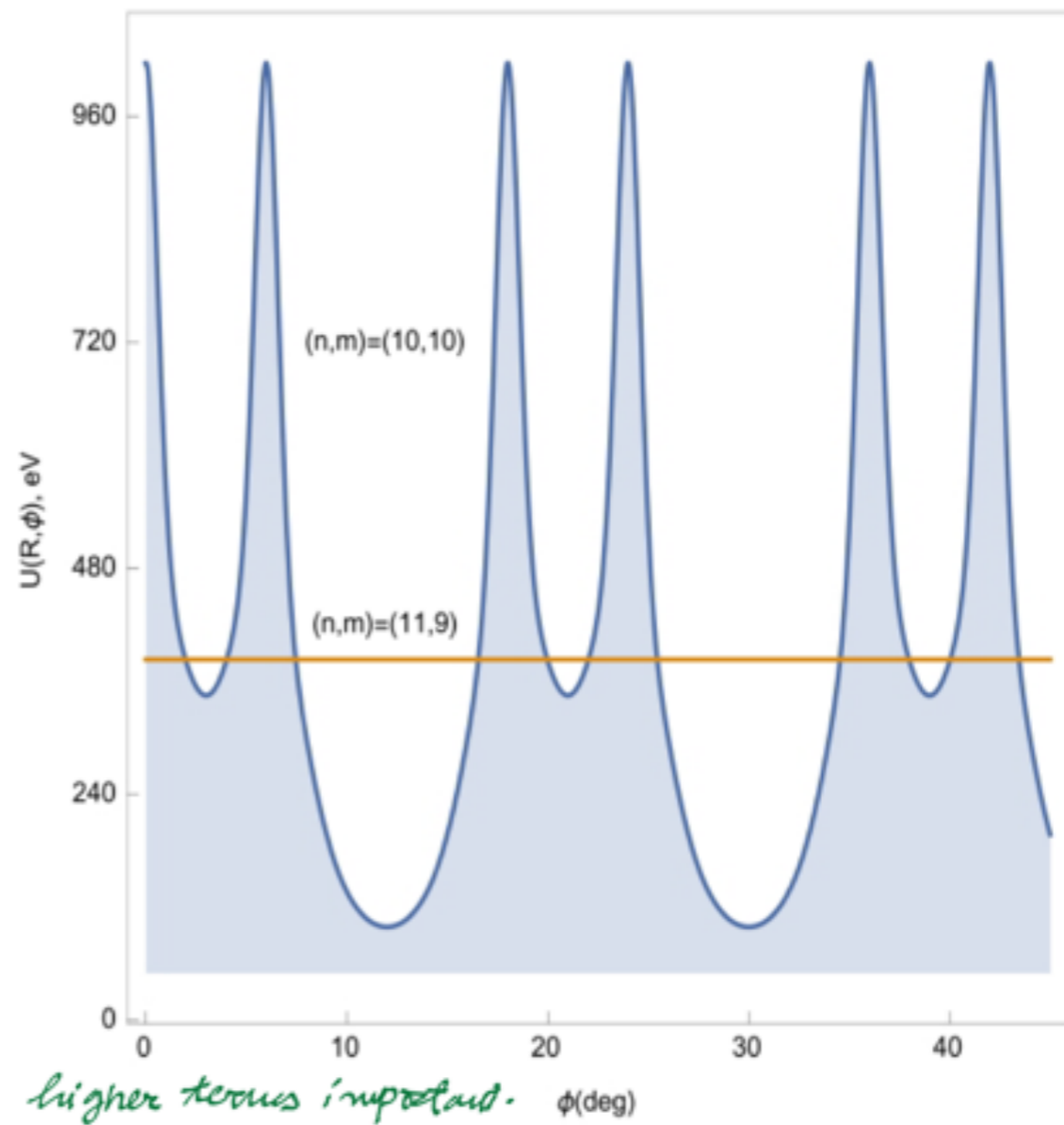
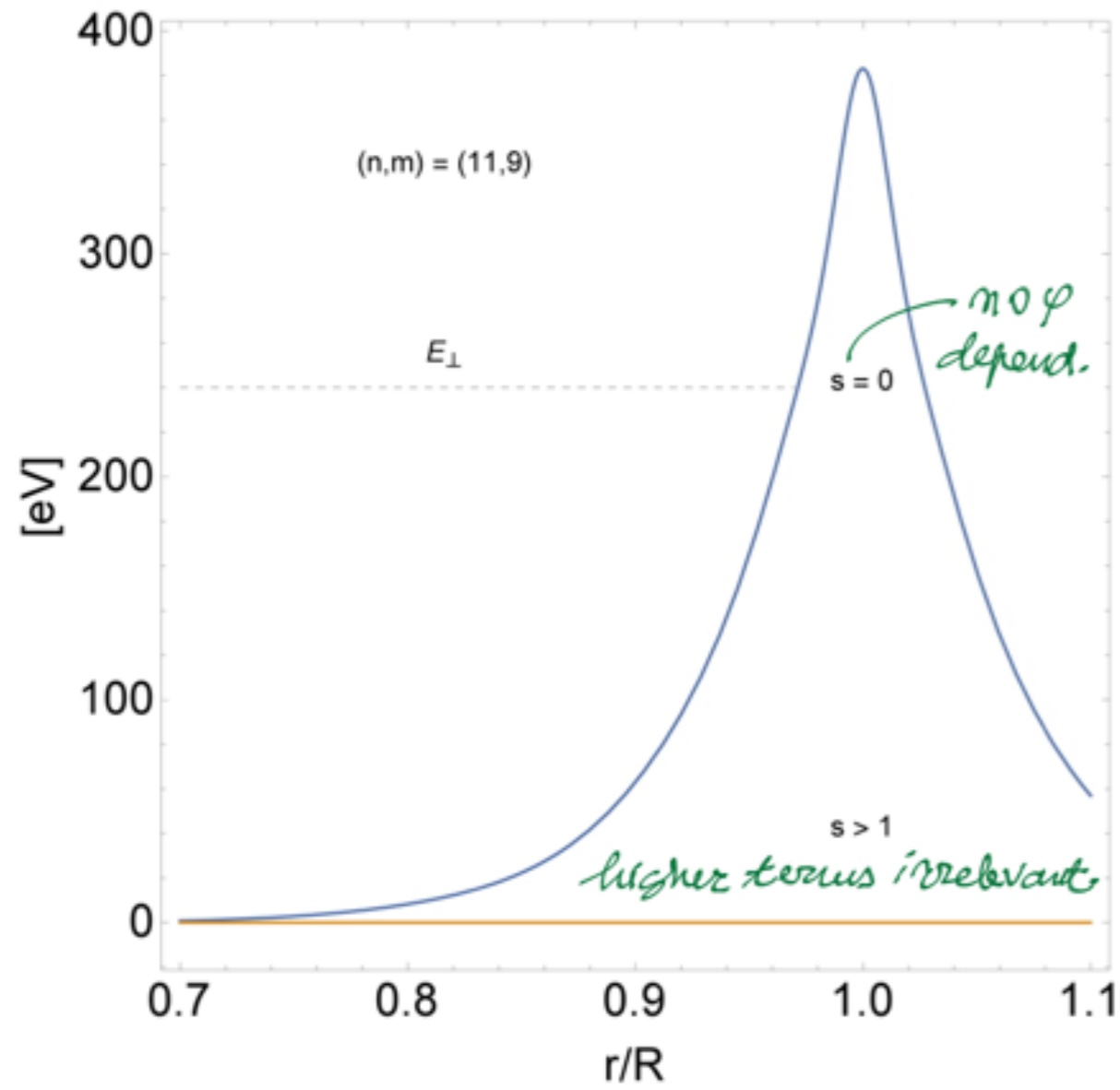
$$\xi = v / 2b_j^2 rR$$

$$\sigma = 4 / e^2 z$$

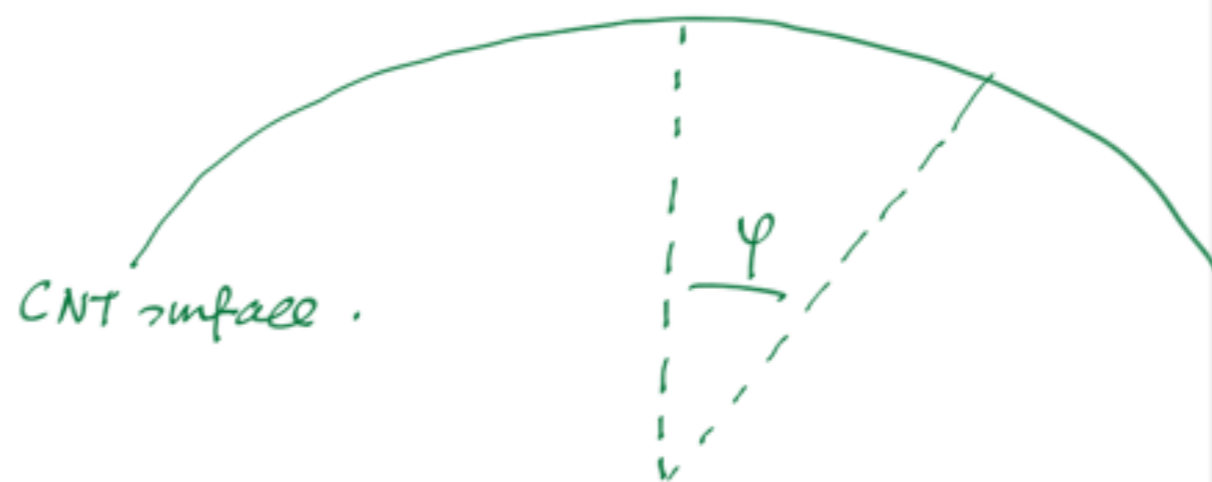
a_j [μm^2], b_j [μm^{-1}] reported in

ARTRU et al. Phys. Rept. 412, 89 (2005)

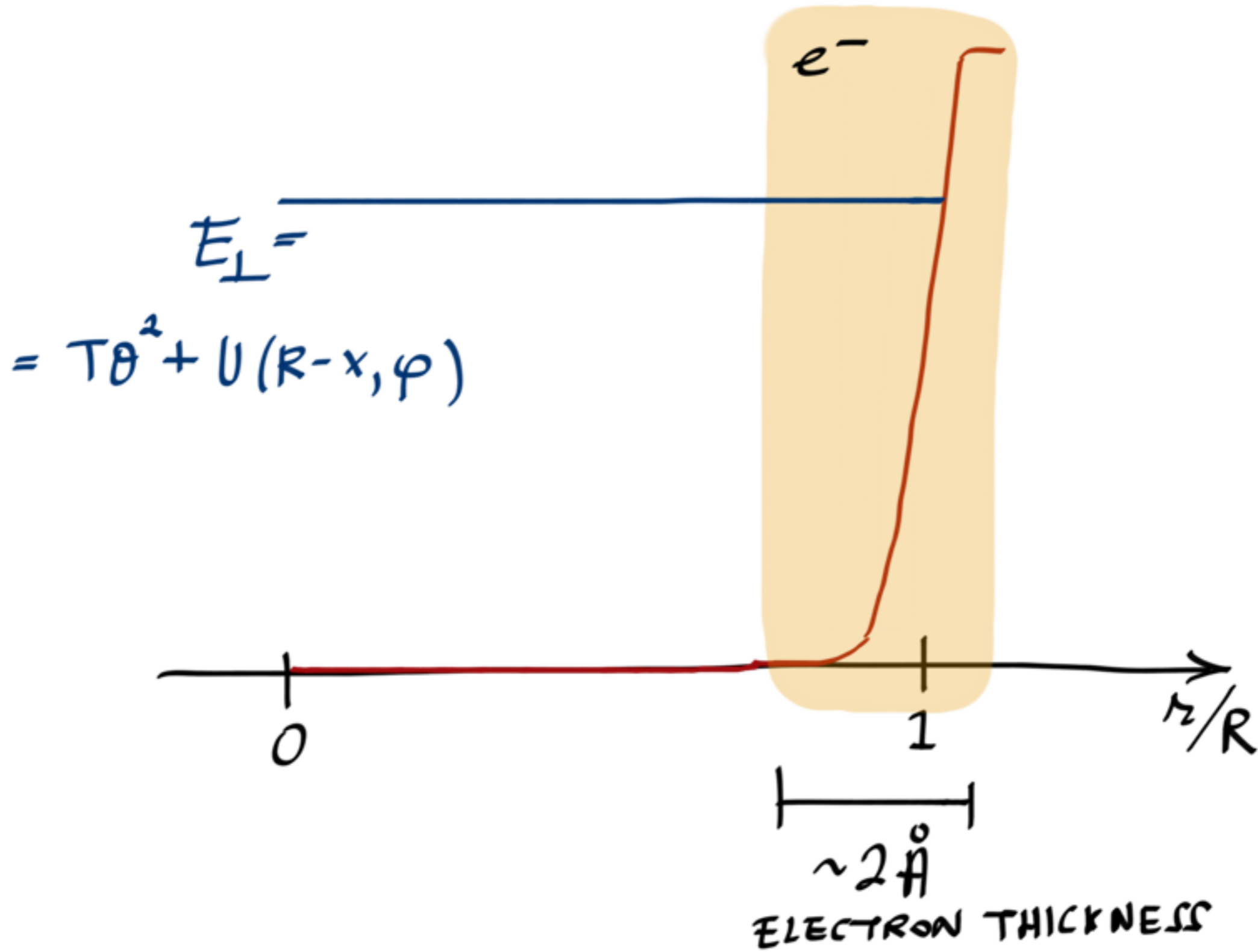
CNT POTENTIALS



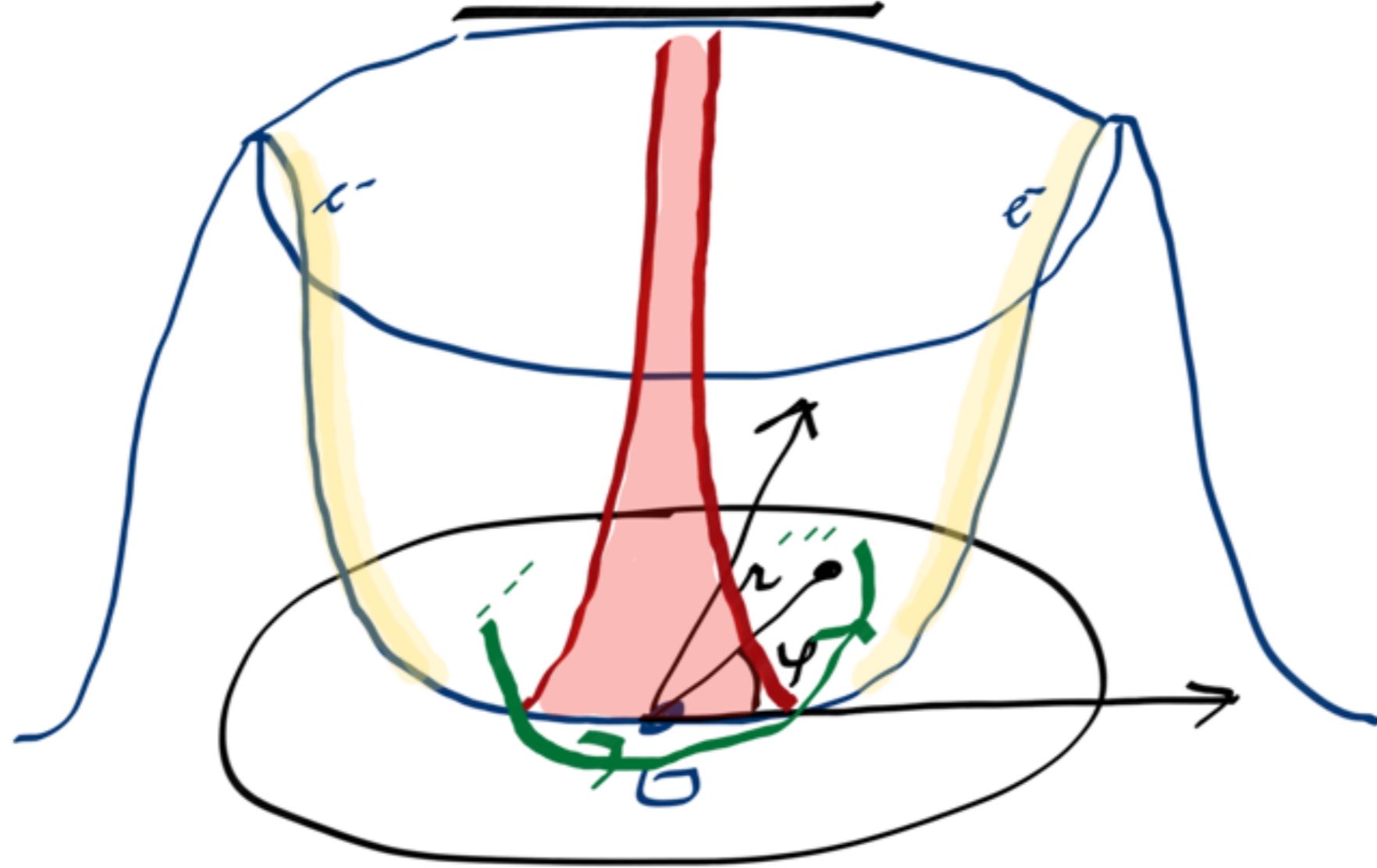
(For a C⁶⁺)



CHANNELS



Paths



If $L = mr^2\dot{\phi}$ is conserved, ϕ changes monotonically along the path in $V \sim V(r) + L^2/2mr^2$.

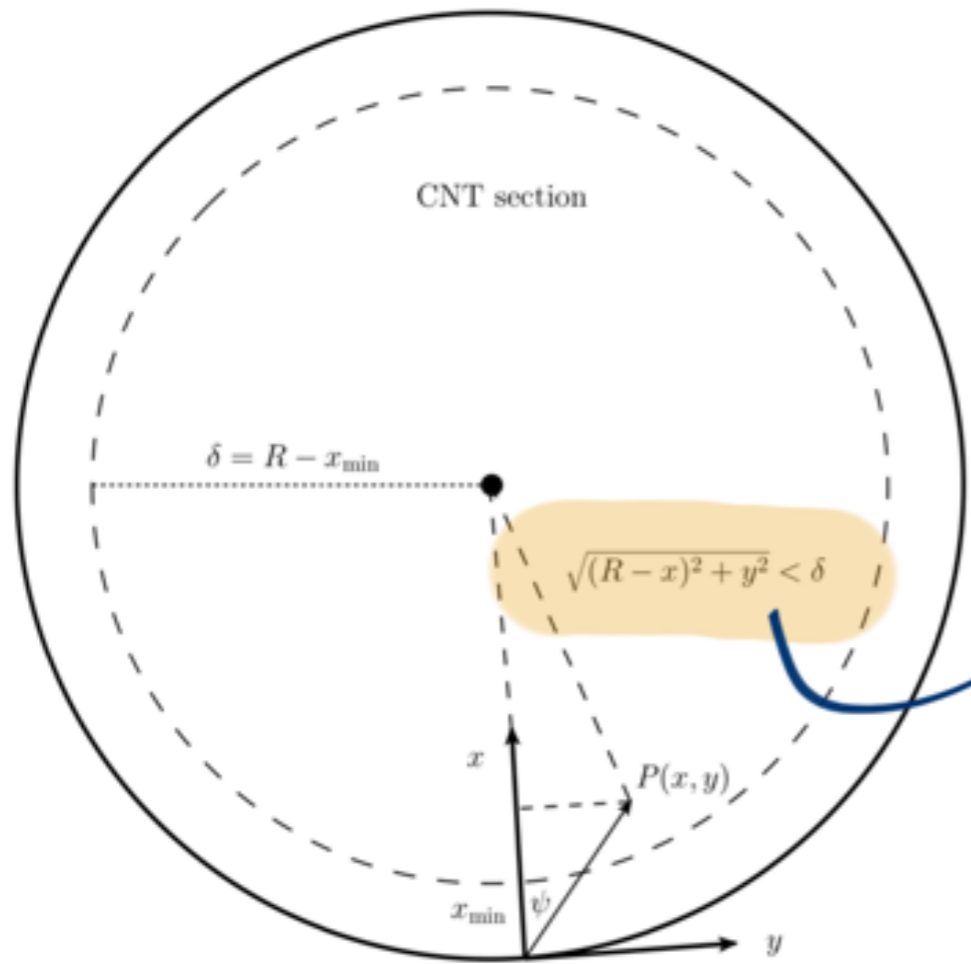
Smaller values of L push closer to the boundaries (where $\dot{r} = 0$)
→ more frequent "dechannelings" or "dead events"

Channelling conditions

$$E_{\perp} = T\theta^2 + U(R-x, \phi) \lesssim \min_{\phi} U(R, \phi)$$

$\Rightarrow x_{min}$

$$W(T, \theta) = \int_{x, y \in \mathcal{R}} \frac{e^{-x^2/2U_{\perp}(T^*)}}{\sqrt{2\pi} U_{\perp}(T^*)} \frac{e^{-y^2/2U_{\parallel}}}{\sqrt{2\pi} U_{\parallel}}$$



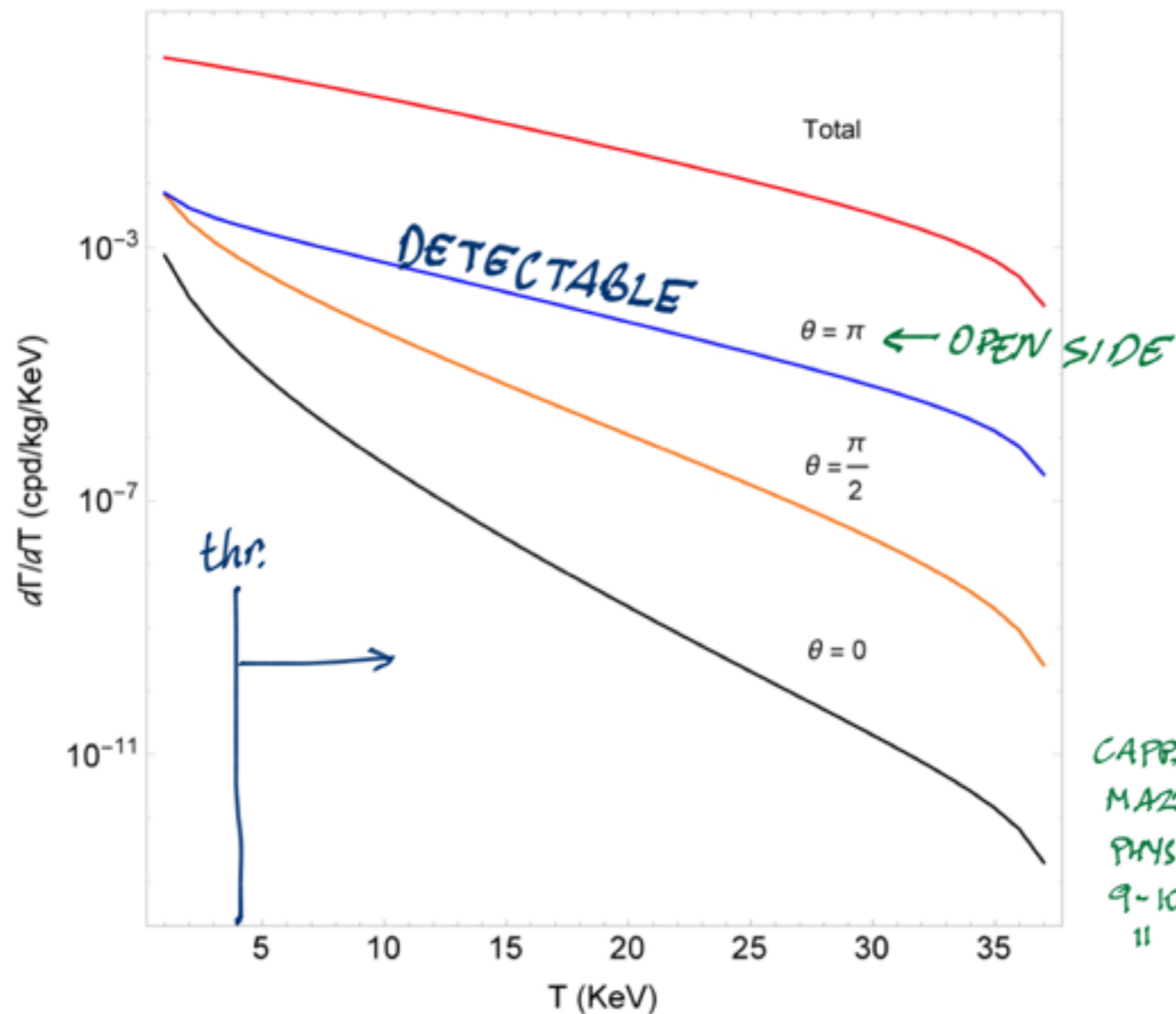
\rightarrow defines \mathcal{R}

$$\left. \begin{aligned} U_{\perp} &= 0.0085 \text{ nm} \\ U_{\parallel} &= 0.0035 \text{ nm} \end{aligned} \right\} @ \text{room } T^*$$

From Debye theory.

A. B. Gelmini
1201.4560

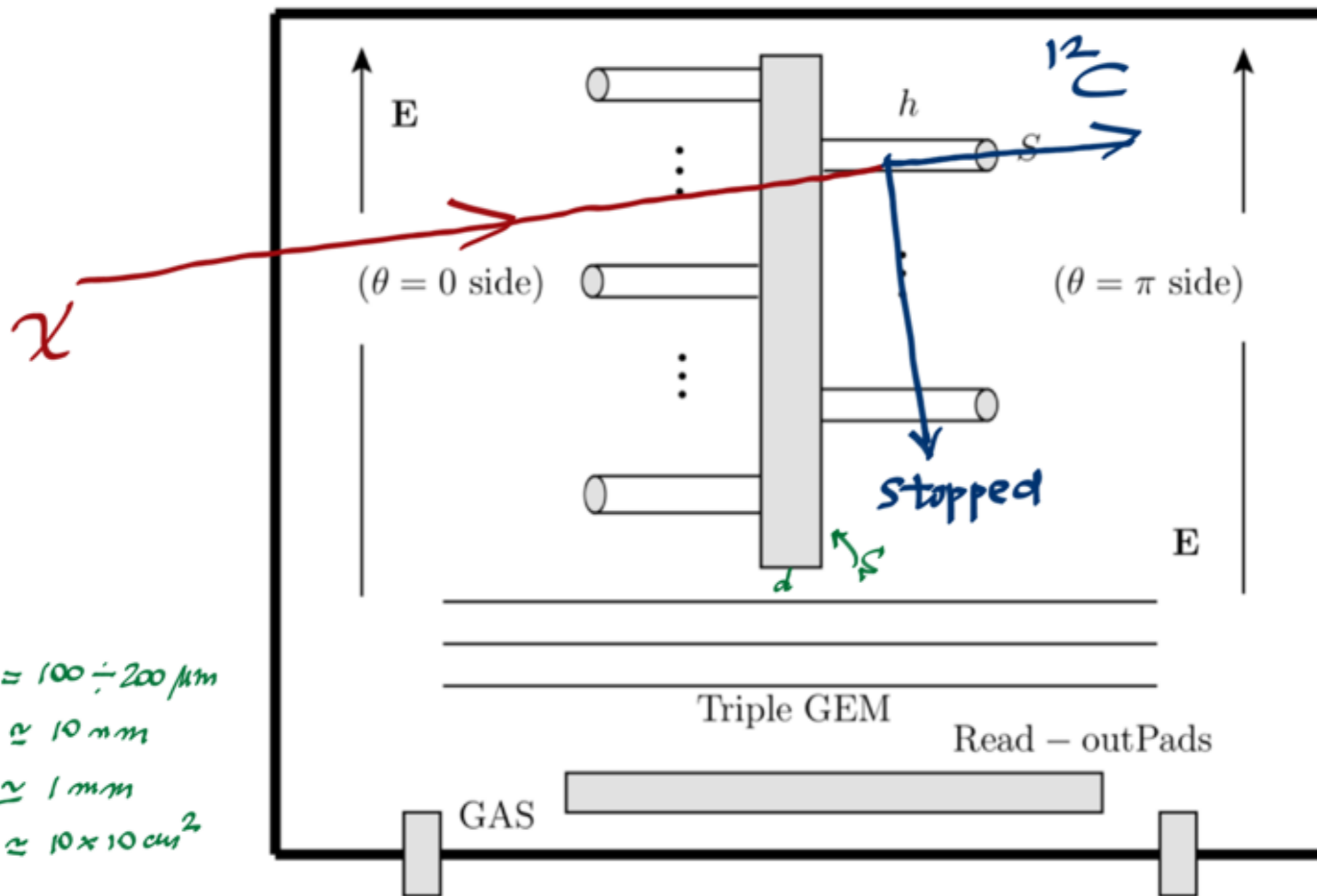
Channelings



$$(n, m) = (73, 71)$$

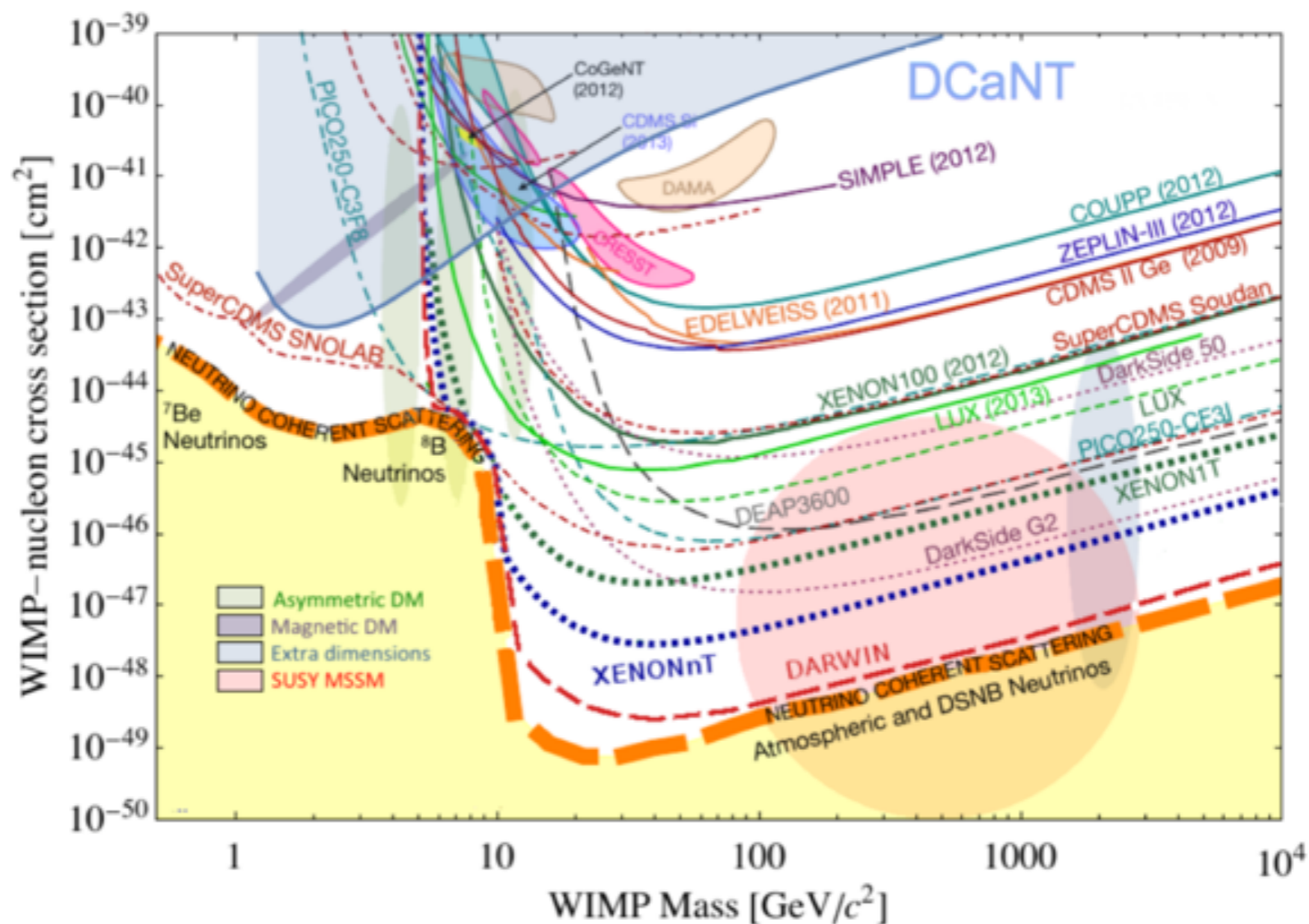
HISTOGRAM OF THE CHANNELLED EVENTS UNDER
 THE VERY RESTRICTIVE CONDITIONS MENTIONED
 BEFORE. RECHANNELINGS OR INTER-CNT
TRAPPING NOT INCLUDED HERE

DIRECTIONAL DETECTOR



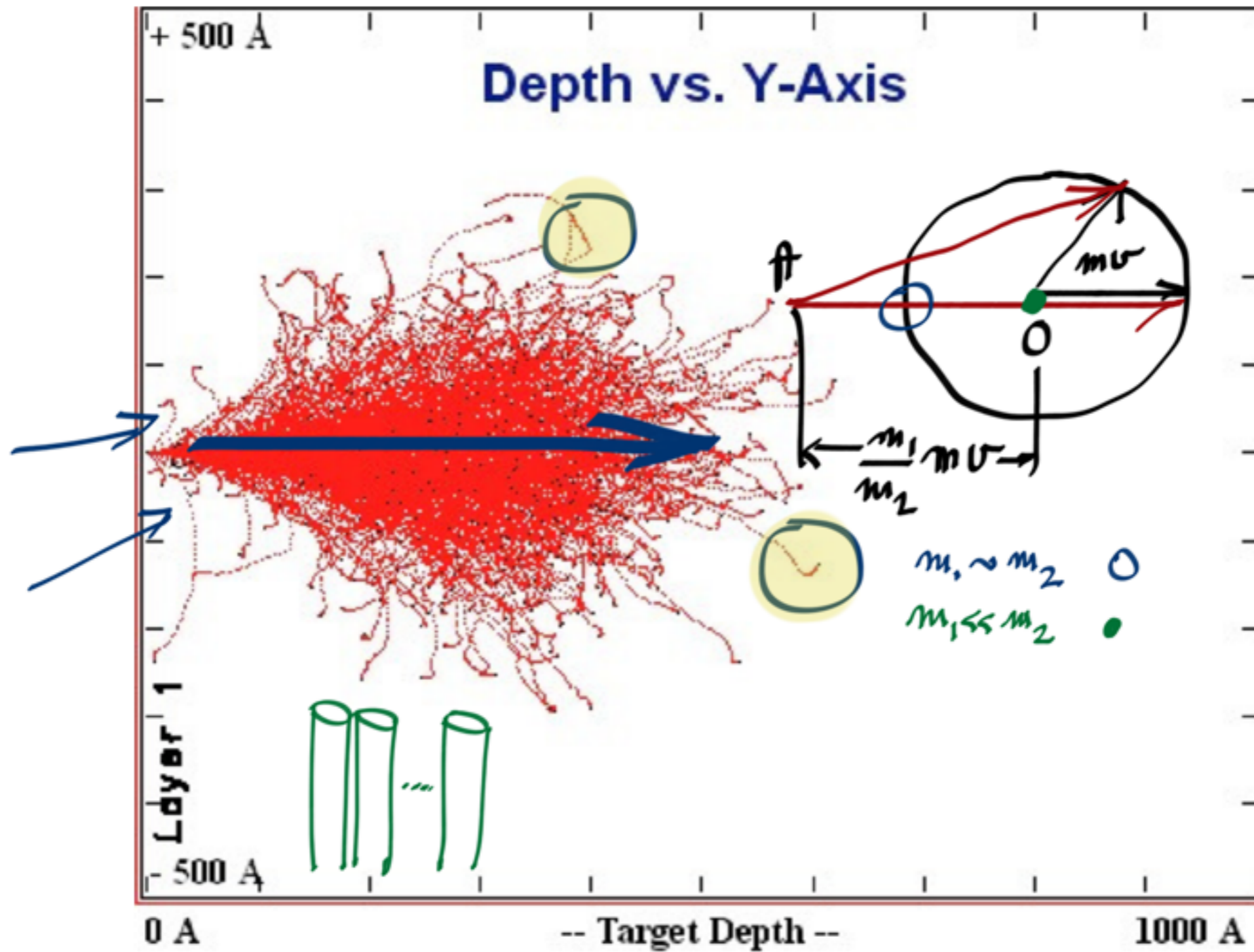
$h = 100 \div 200 \mu\text{m}$
 $\phi \approx 10 \text{ mm}$
 $d \approx 1 \text{ mm}$
 $S \approx 10 \times 10 \text{ cm}^2$

Sensitivity



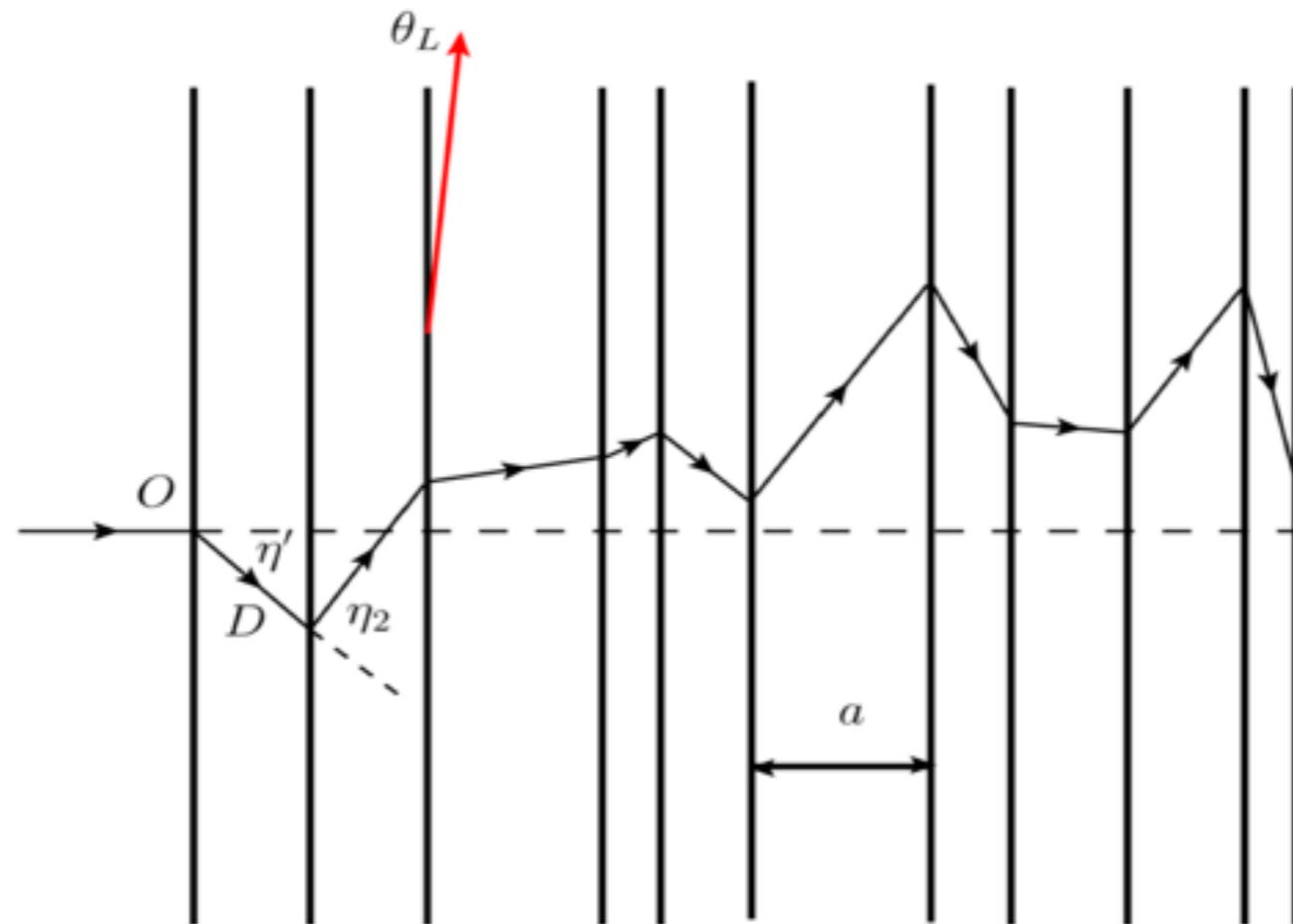
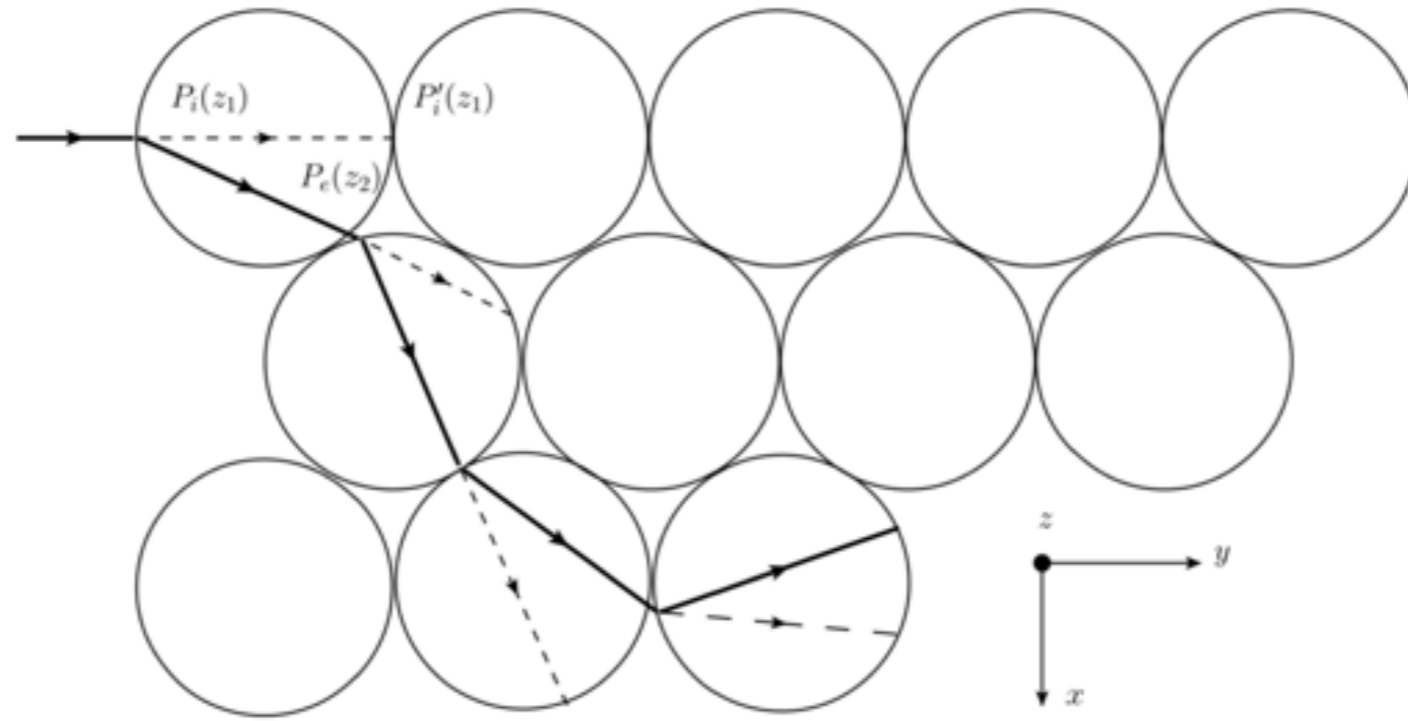
- 100 layers, 1m² each
- Compact readout → few m³ volume
- Rotated tracking CYGNUS
- Sensitivity for 0.4 Kg y
 (CNT trapping C ions detected down to 1keV)

RE-CHANNELINGS

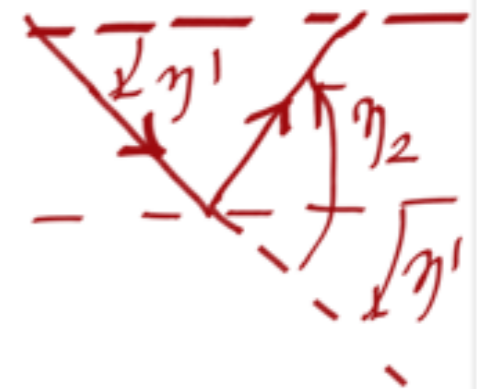


θ_s from dist. $\cos \theta_s / \sin^3 \theta_s$ ($m_1 \sim m_2$)

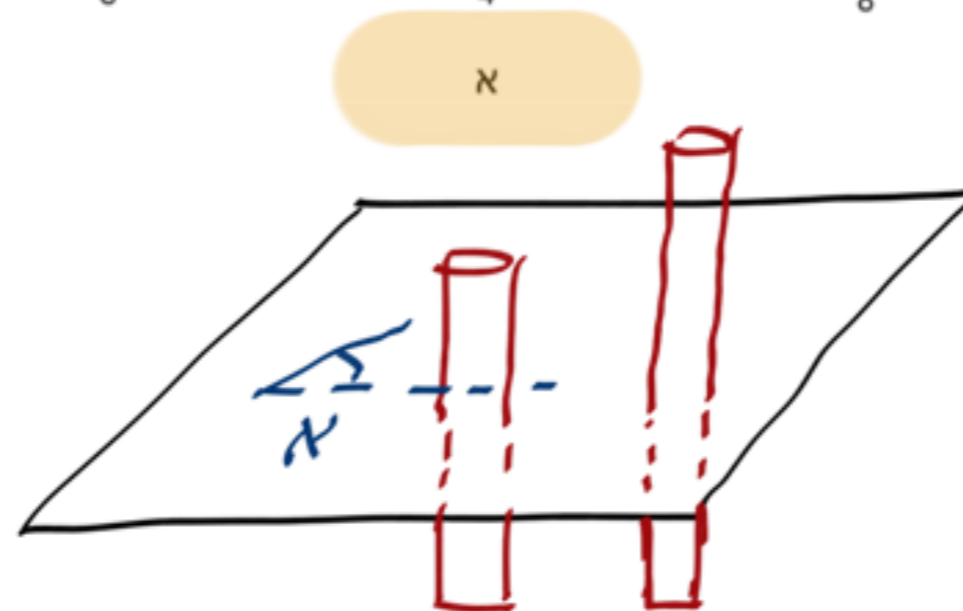
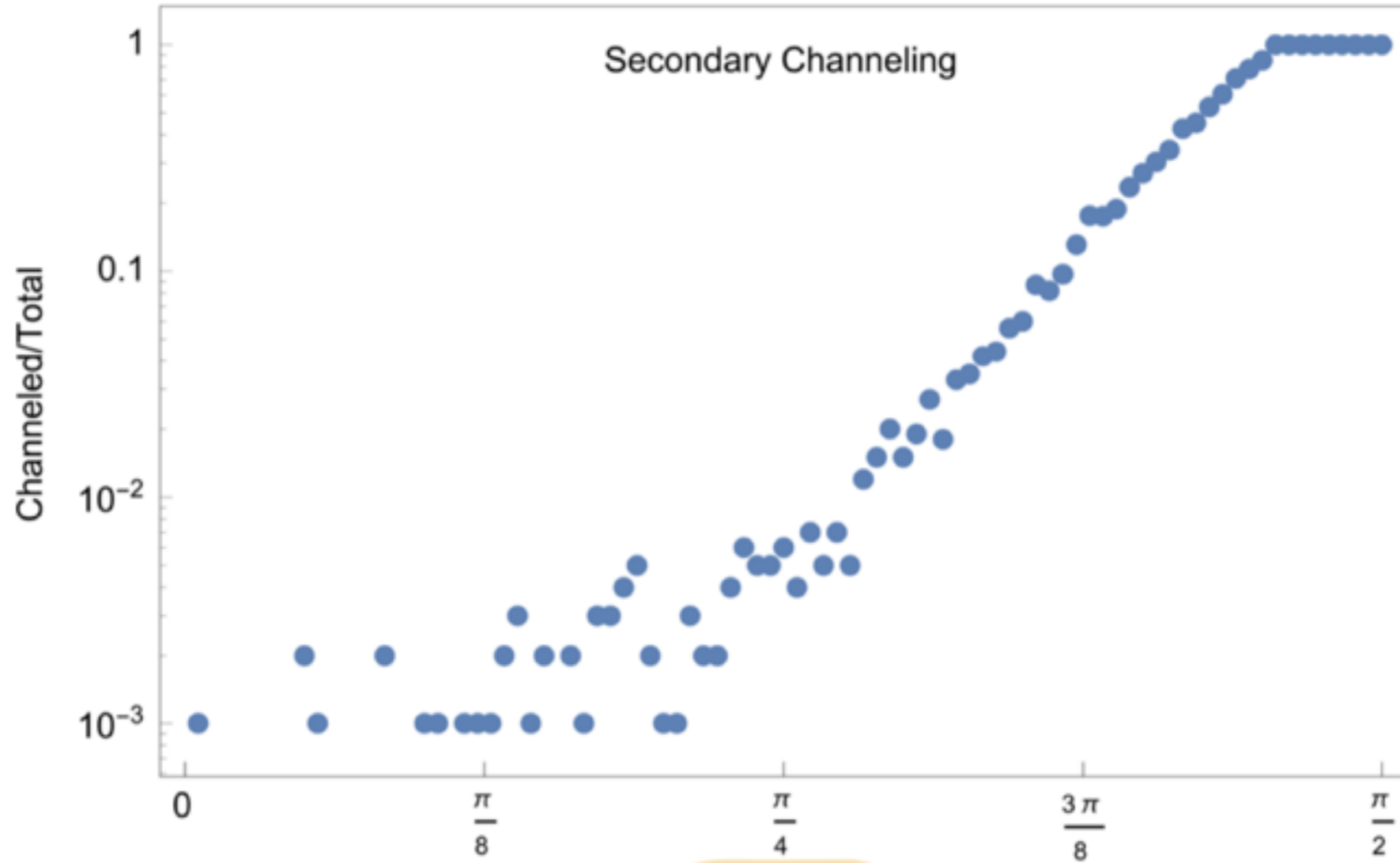
RE-CHANNELINGS



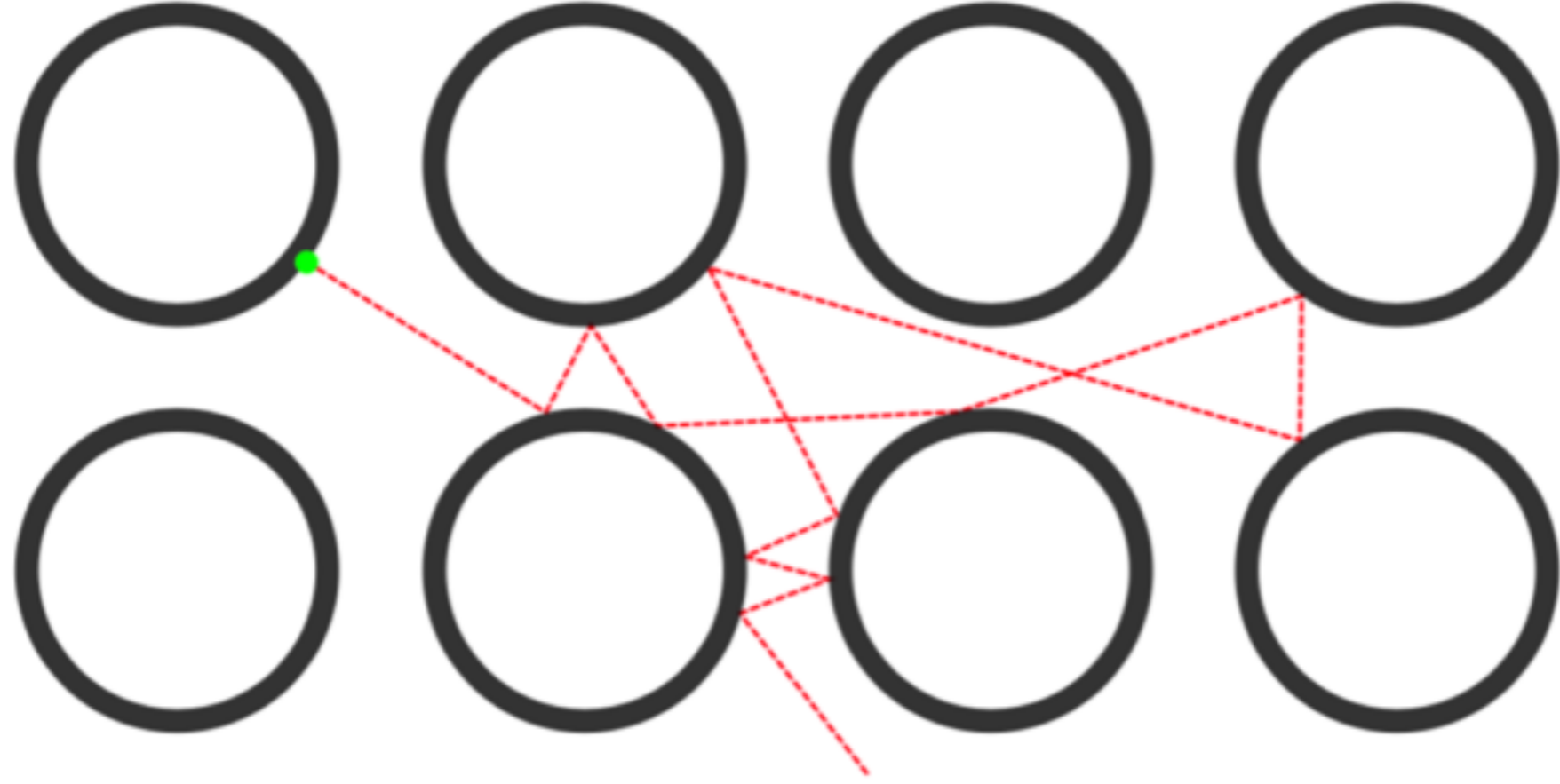
**PROJECTED
SCATT. ANGS.**



RE-CHANNELINGS



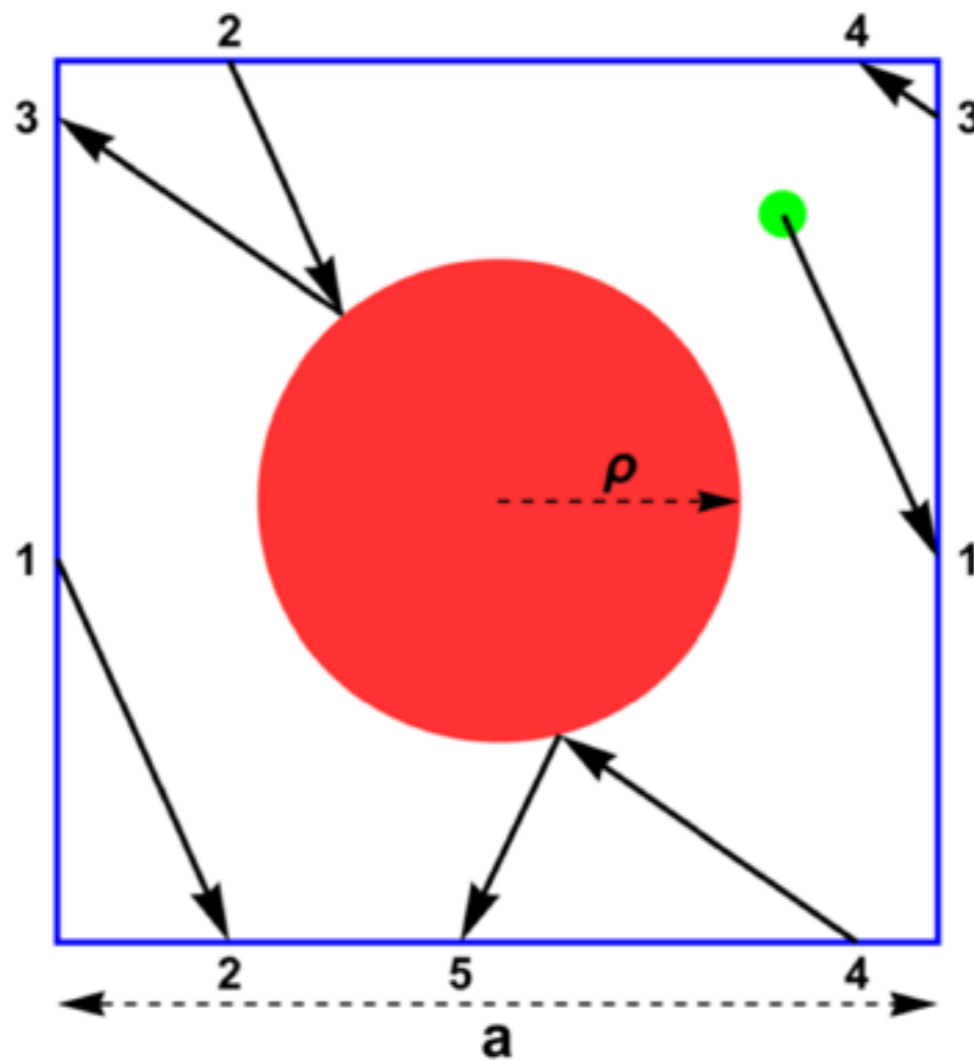
Billiards



Billiards

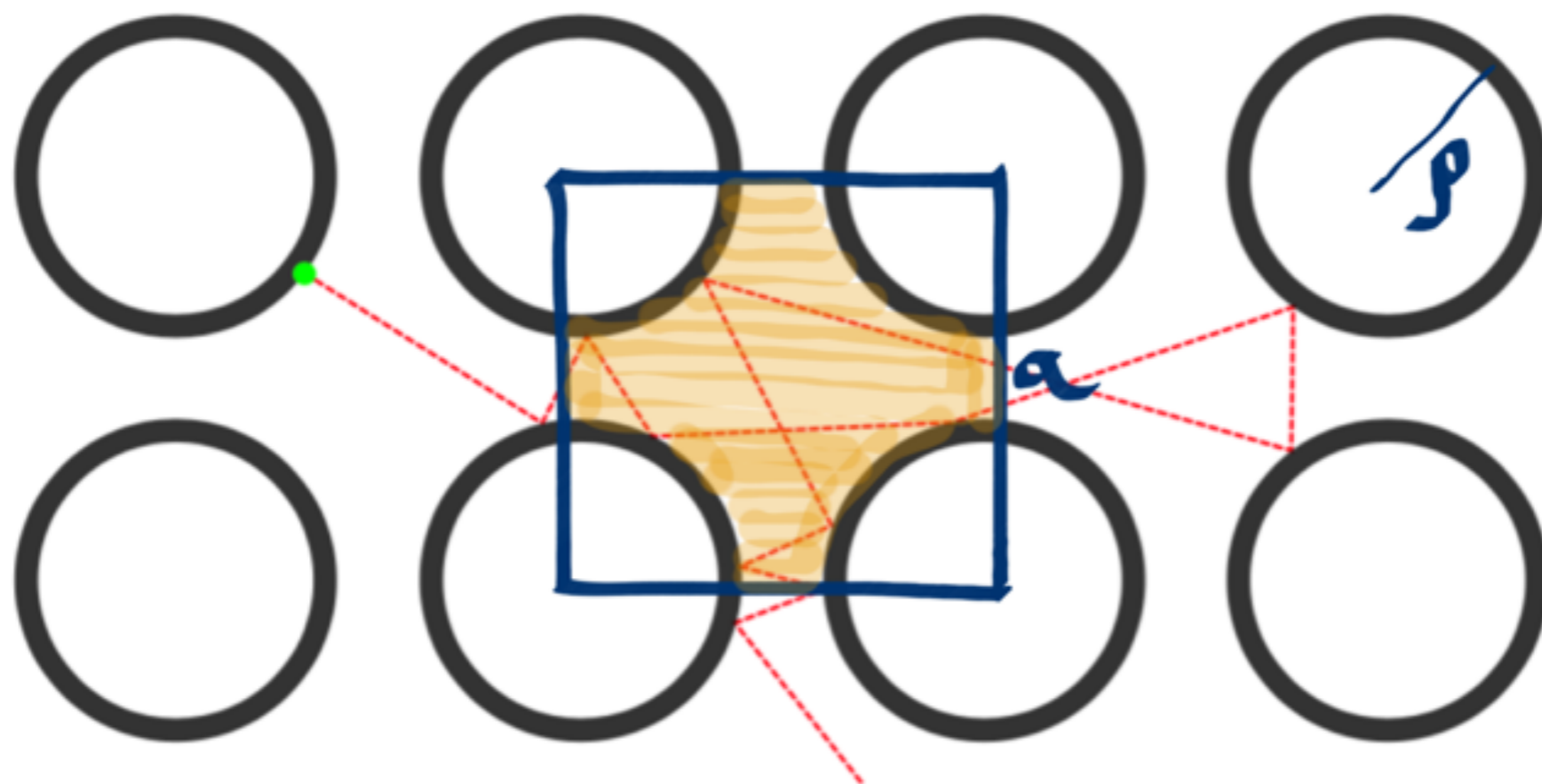
Problem: a particle enters the CNT forest with (v_1, v_2) .

WILL IT REACH THE (OPEN) TOP OF THE FOREST BEFORE EXITING FROM SIDES?



Billiards

$$\tau = N_{\text{hops}} \tau_R$$

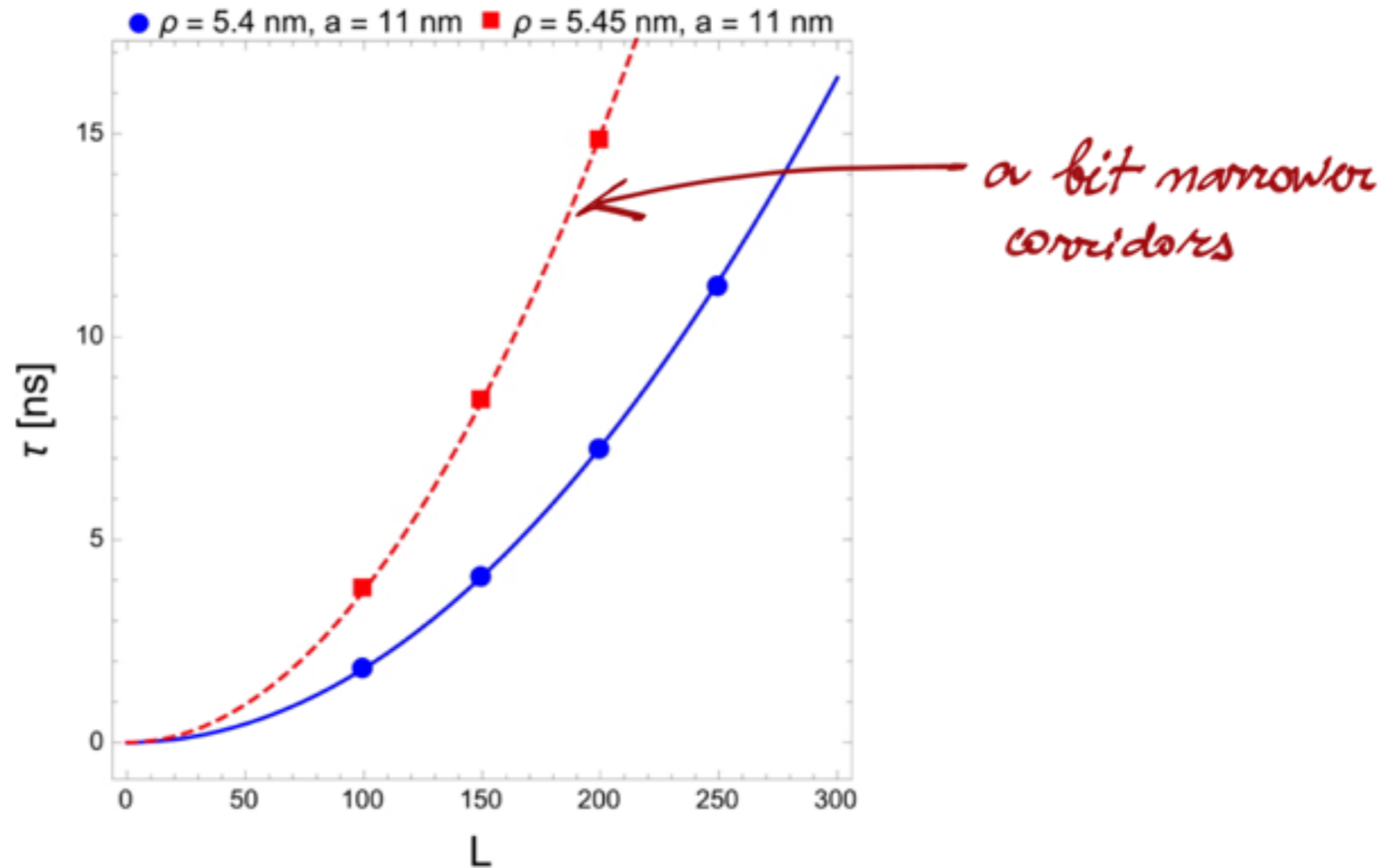


$$\delta = a - 2p$$

$\delta \ll a = \text{NARROW CORRIDOR REGIME}$

$$\tau_R = \frac{\pi (a^2 - \pi p^2)}{4 v_{\perp} \delta}$$

Billiards



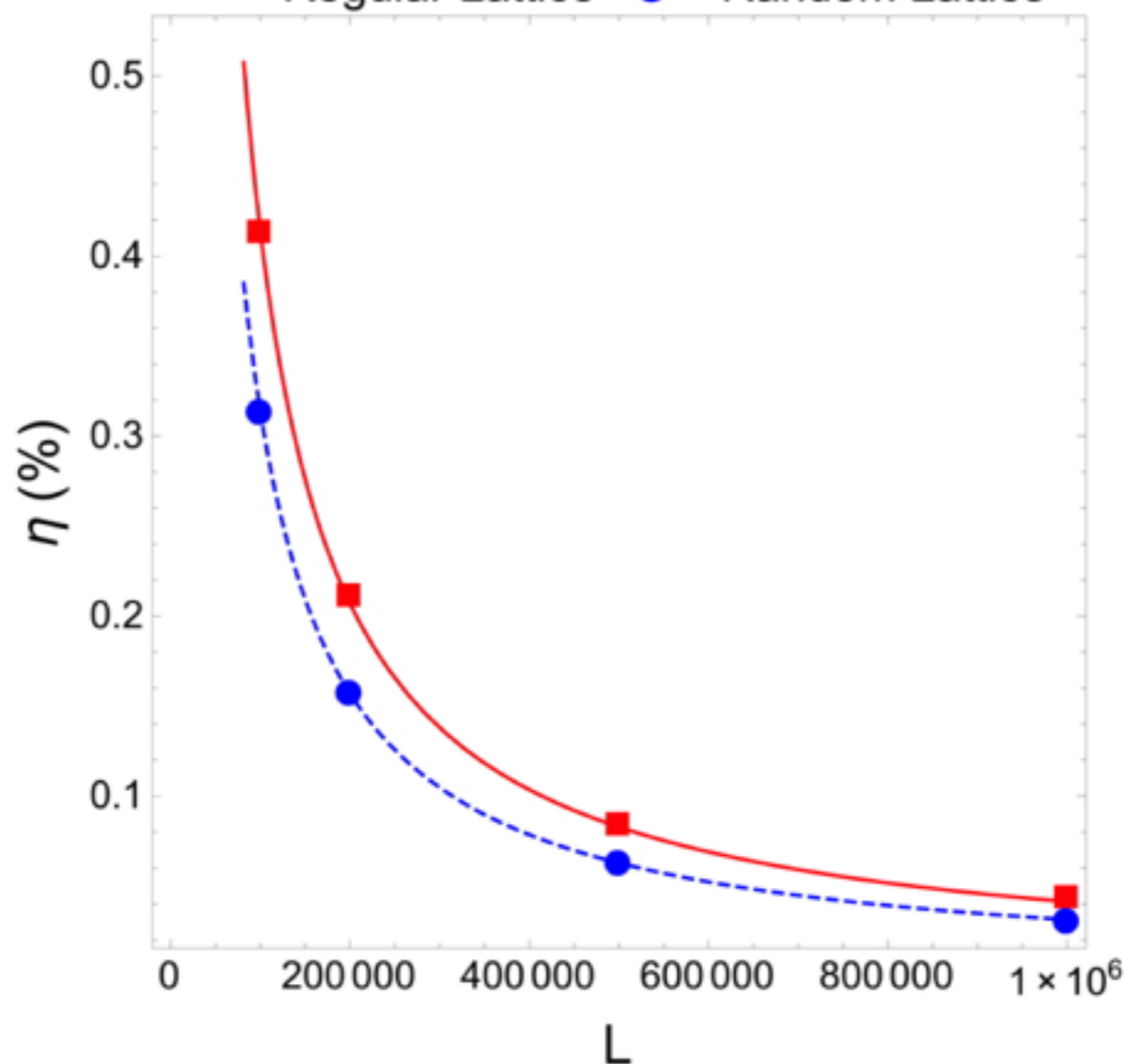
find $n_h \approx \frac{L^2}{\tau}$; $E_{\perp} \approx 300 \text{ eV}$

τ = time needed to exit from the billiard.
MEAN EXIT TIME

Lateral losses

$E_{\parallel}=1$ keV, $E_{\perp}=300$ eV, $h = 300 \mu\text{m}$

■ = Regular Lattice ● = Random Lattice



$\eta =$ FRACTION OF PARTICLES LEAVING FROM SIDES BEFORE REACHING THE TOP

$$\eta \sim L/h^2 \sim 1/L \quad (\approx 300 \div 400/L)$$

TYPICAL $L > 10^5$

Energy losses

WE FIND HOWEVER THAT THE IONS MAY LOOSE UP TO 4 keV ON THEIR WAY TOWARDS THE TOP OF THE ARRAY - in going from interstices to the interior of tubes and back

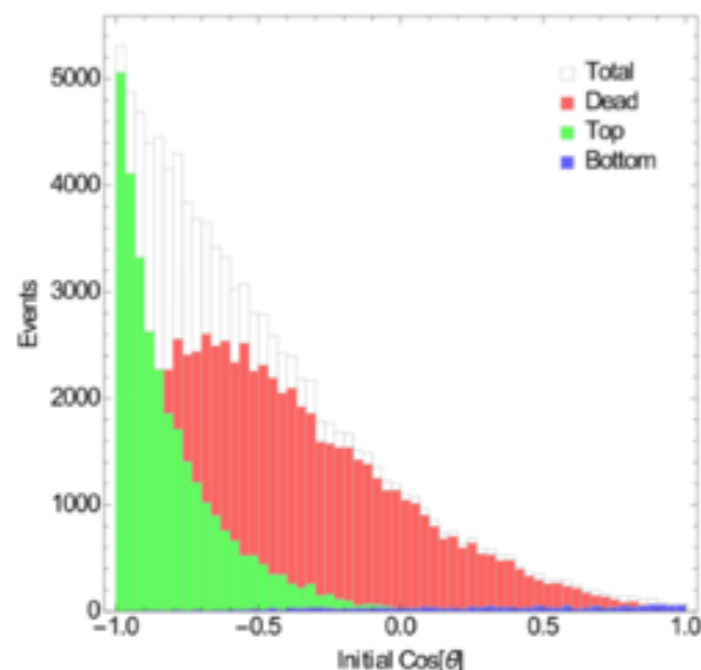
- 1) Top events: exit from the open end of the array with $E_{||} > 1 \text{ keV}$
- 2) Bottom events: opposite
- 3) Dead events: ions reach energies below det. threshold while traveling in the array
- 4) Side events: lateral losses

With 10^5 ion trajectories we get

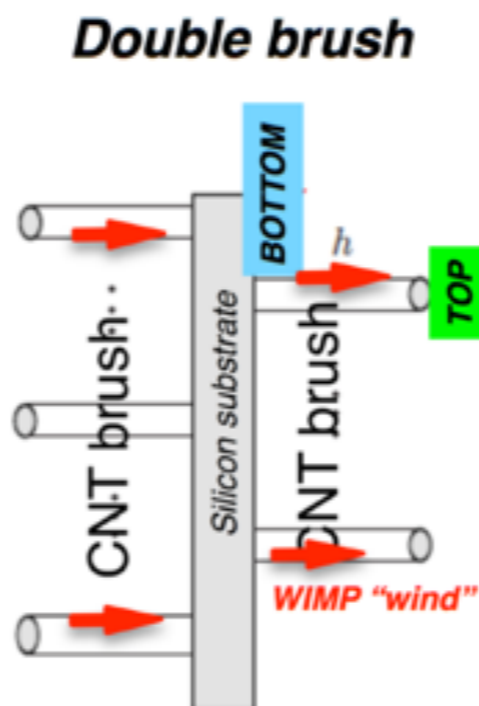
Top	Bottom	Side	Dead	Total
30802	1786	447	66965	100000

$\sim 1/20$

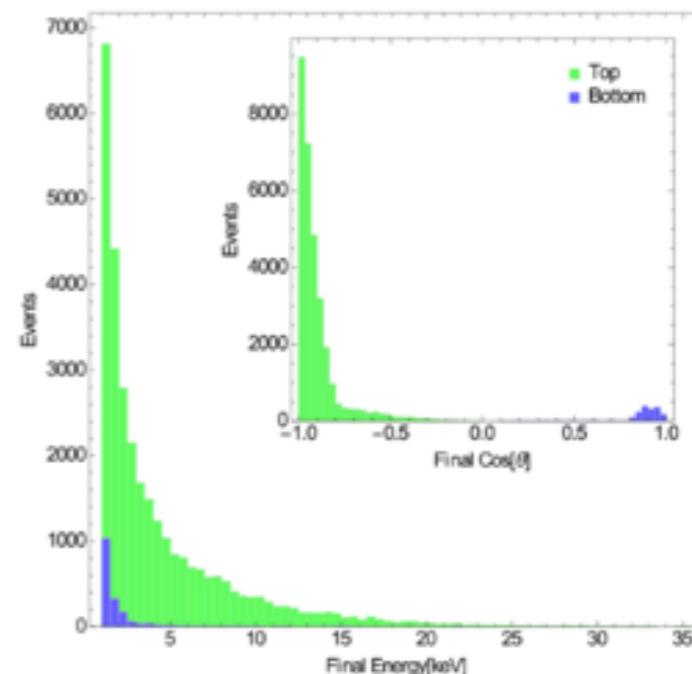
Energy losses



Initial C ion direction



Double brush



Final C ion energy and direction

CAVOTO, COCINA, FERRETTI, POLOSA arXIV: 1602.03216

- After a WIMP scattering event, the fraction of ions channeled in a single CNT is $\approx 0.4\%$.
- Remaining ones are scattered outside of the CNT

However the CNT ARRAY might COOPERATE to recover part of the would-be-lost particles guiding them to the top.

$$\theta_A \sim 4^\circ \text{ CNT} \rightarrow \theta_A \sim 35^\circ \text{ CNT ARRAY}$$



CYGNUS-TPC proposal



Galactic Nuclear Recoil Observatory: **measure WIMP and coherent neutrino scattering from the Sun** with:

- Recoil direction sensitivity
- keV-scale threshold (10 keV in the plots)**
- Full 3D fiducialization
- TPCs distributed in 5 underground sites scattered around the globe



Pathfinder approach (optimize readout and engineering)

- CYGNUS-P1**: 24 m³ Large Volume (**10Kg target mass**) with already existing technology + **1 m³ High Definition pixelized readout (CNT ?)**
- CYGNUS-P2**: down-selected technology for engineering optimization (400 kg)
- CYGNUS-TPC**: Galactic Observatory w/ multiple light target nuclei (1.2 ton)

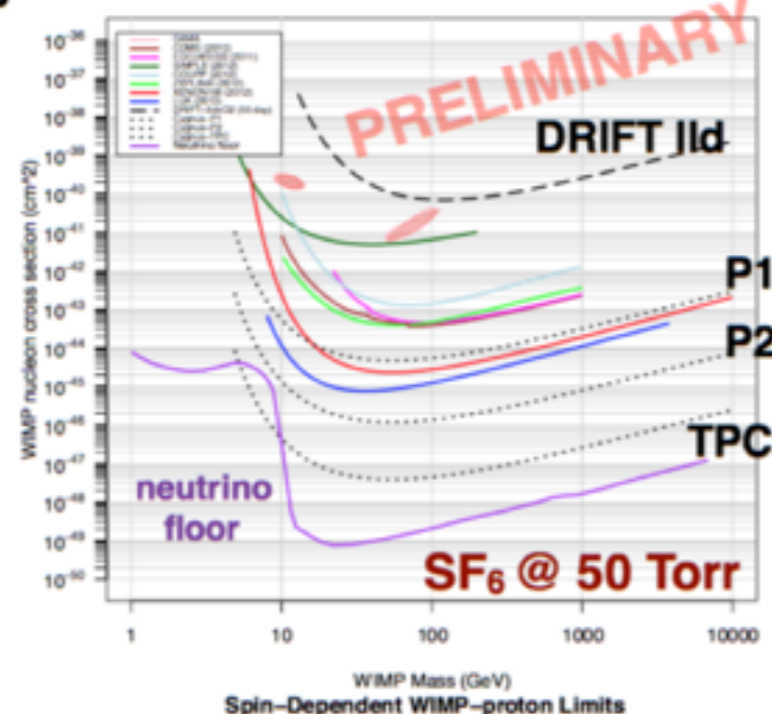
Building an international collaboration from various directional DM TPC groups to prepare LOI
DRIFT + NEWAGE + D³ + DMTPC + MIMAC + NITEC
UK + USA + Japan + Australia + Italy?

"CYGNUS-TPC kick-off meeting: a mini-workshop on directional DM search and coherent neutrino scattering"

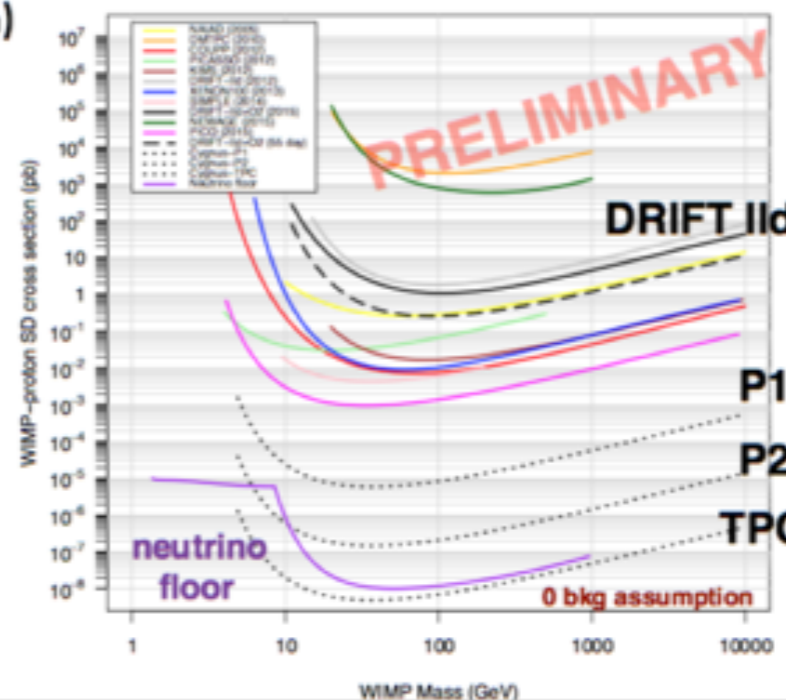
7th-8th April 2016, Laboratori Nazionali di Frascati

<http://www.lnf.infn.it/~baracch/index.html>

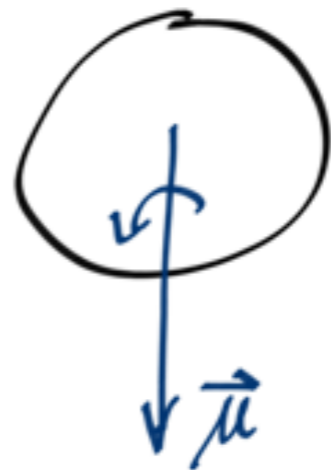
Spin-Independent WIMP Limits



Spin-Dependent WIMP-proton Limits



AXION-LIKE PARTICLES
with m_b THE photons



$\bar{\Psi} \sigma^{ij} \Psi \cdot F_{ij}$ CP-even coupling.



$\bar{\Psi} \sigma^{ij} \Psi \cdot F_{ij}$ CP-odd
 $(\vec{\sigma} \cdot \vec{\mu})$

QCD action contains a CP odd term (euclidean)

$$i\theta q[A]$$

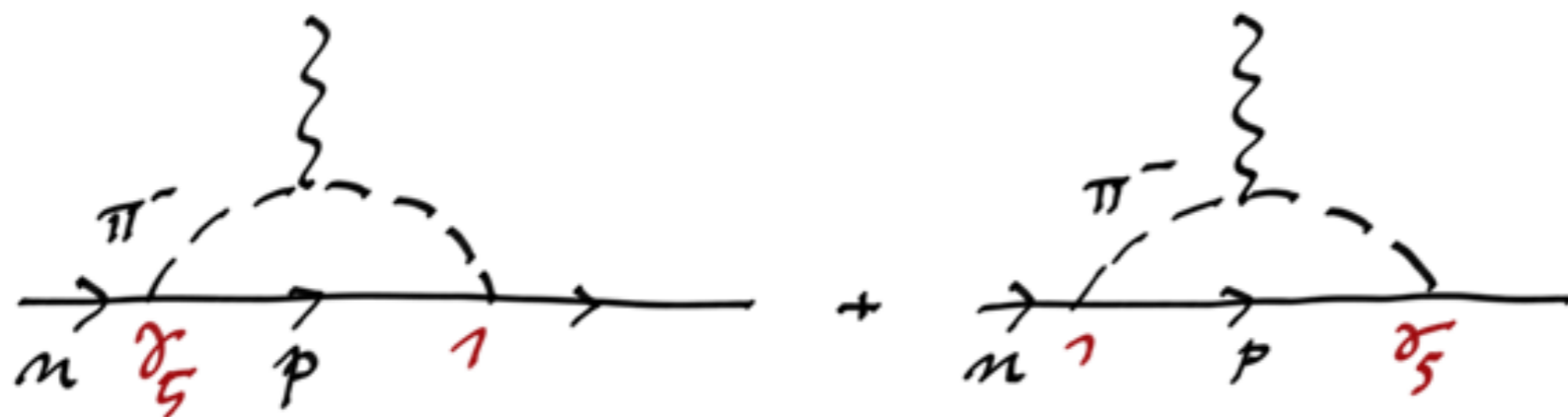
where

$$q[A] = \frac{g_0^2}{32\pi^2} \int F \cdot \tilde{F} d^4x$$

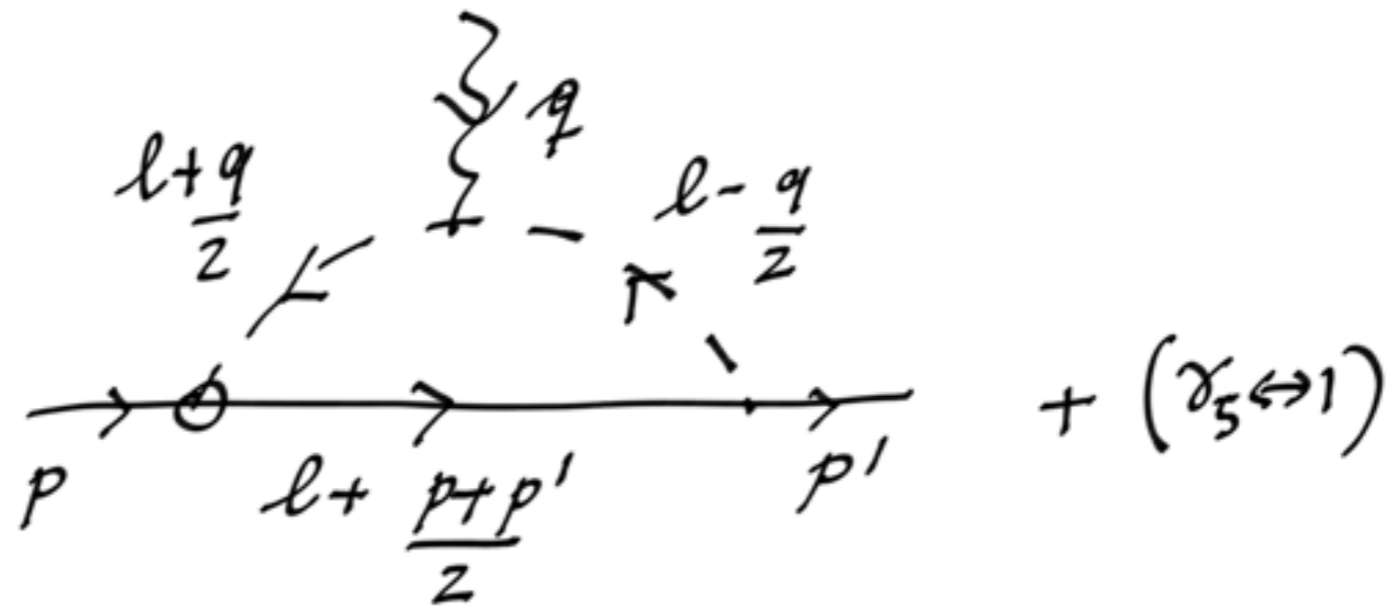
which induces a CP-odd term in the low energy theory

$$\begin{aligned} \mathcal{L}_{\pi NN} = & g_{\pi NN} \bar{\Psi} \gamma_5 \vec{\sigma} \Psi \cdot \vec{\pi} \\ & + g'_{\pi NN} \bar{\Psi} \vec{\sigma} \Psi \cdot \vec{\pi} \end{aligned}$$

Consider a gg' amplitude



separation of charge



$$\sim \left(\bar{u}(\vec{p}') i \sigma^{\mu\nu} q_\nu \gamma_5 u(\vec{p}') \right) \epsilon_\mu(q)$$

$$\sim \tilde{F}_{\mu\nu} \bar{\psi} \sigma^{\mu\nu} \psi$$

δ - π coupling ensures a $\ln \frac{\Lambda^2}{m_\pi^2}$ enhancement
 where $\Lambda = 4\pi f_\pi$

$$g' \simeq \frac{\theta \zeta}{f_\pi} \quad \text{where} \quad \zeta \simeq \frac{m_u m_d}{m_u + m_d}$$

$$g \simeq \frac{g_A m_N}{f_\pi} \quad \text{where} \quad g_A = 1.27$$

Dependency on light quark masses

$$Z_\theta = N \int DA e^{-\frac{1}{4}(F,F) - i\theta q[A]} \int D\Psi D\bar{\Psi} e^{-(\bar{\Psi}, (D+M)\Psi) - (\eta, \bar{\Psi}) - (\bar{\eta}, \Psi)}$$

One can set $\theta=0$ just chiral rotating sources.

If $q=1$, set $\alpha = \frac{\theta}{2N_f}$ to get $\theta=0$.

However

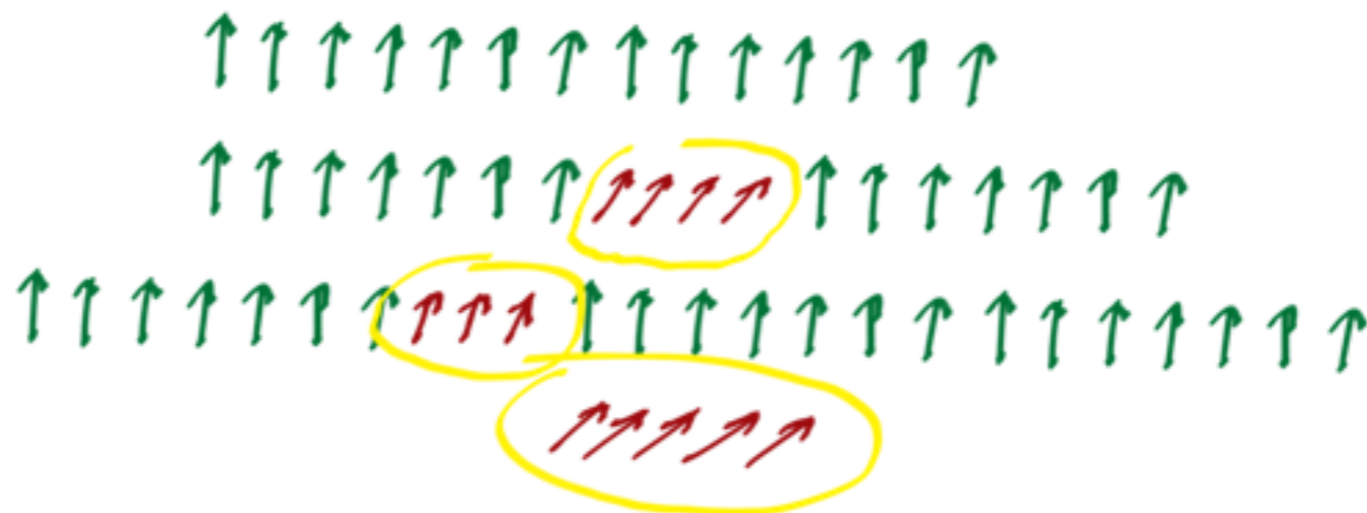
$$M \rightarrow M' = e^{-2i\alpha \gamma_5} M$$

So M' depends on θ , and

$$M' = A' + i\gamma_5 B' \quad (A', B' \text{ hermitian})$$

and require

$$\langle \pi | \bar{\Psi} i\gamma_5 B' \Psi | 0 \rangle = 0$$



FROM THE MEASUREMENT OF d_n ($\lesssim 6 \times 10^{-26} \text{ e} \cdot \text{cm}$)

$$|\theta| < 10^{-10}$$

Either $m_\nu \equiv 0$ or there is a dynamical reason setting $\theta \rightarrow 0$.

$$\theta F \tilde{F} \longrightarrow (\theta + a/f) F \tilde{F}$$

where a is a new pseudoscalar field with a potential $V(a)$.

The minimum is at

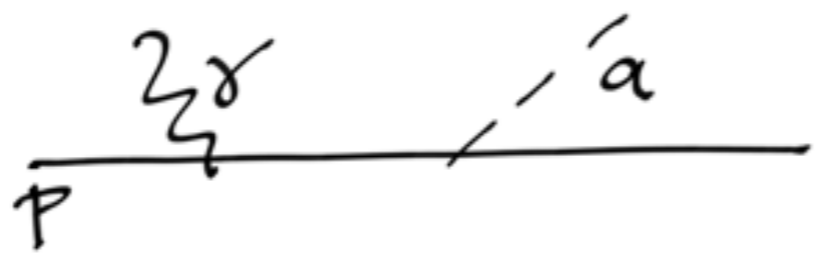
$$a = -f\theta (+ \tilde{a})$$

From the \tilde{a}^2 term one gets

$$m_a^2 = \frac{m_\pi^2 f_\pi^2}{f^2} \frac{m_\nu m_d}{(m_\nu + m_d)^2}$$

All axion couplings are $1/f$ suppressed (Goldstone)

- AXIONS CAN BE COPIOUSLY PRODUCED IN THE EARLY UNIVERSE — if a certain upper bound is saturated ($f \lesssim 10^{11}$ GeV), they can constitute DM.
- A lower bound ($f \gtrsim 10^{10}$ GeV) from astrophysics.



$$\text{Rate} \sim \frac{\alpha}{f^2} \cdot n_\gamma \sim \frac{\alpha}{f^2} T^3 \quad (T \sim 1 \text{ MeV})$$

$$R = \text{Rate}/V \sim n_p \frac{\alpha}{f^2} T^3 \quad \left(n_{e,p} = \frac{\#e}{R_{\text{Sun}}} \approx 3 \times 10^{17} \text{ GeV}^3 \right)$$

hydrogen

$$R = \frac{2.2 \times 10^{-28}}{f^2} \text{ GeV}^4$$

$$R_\nu = (G_F^2 E^2) n_e^2 = 1.2 \times 10^{-49} \text{ GeV}^4$$

Require $R_\nu \sim R \rightarrow f \sim 10^{10} \text{ GeV} \quad m_a \approx 2 \text{ meV}$

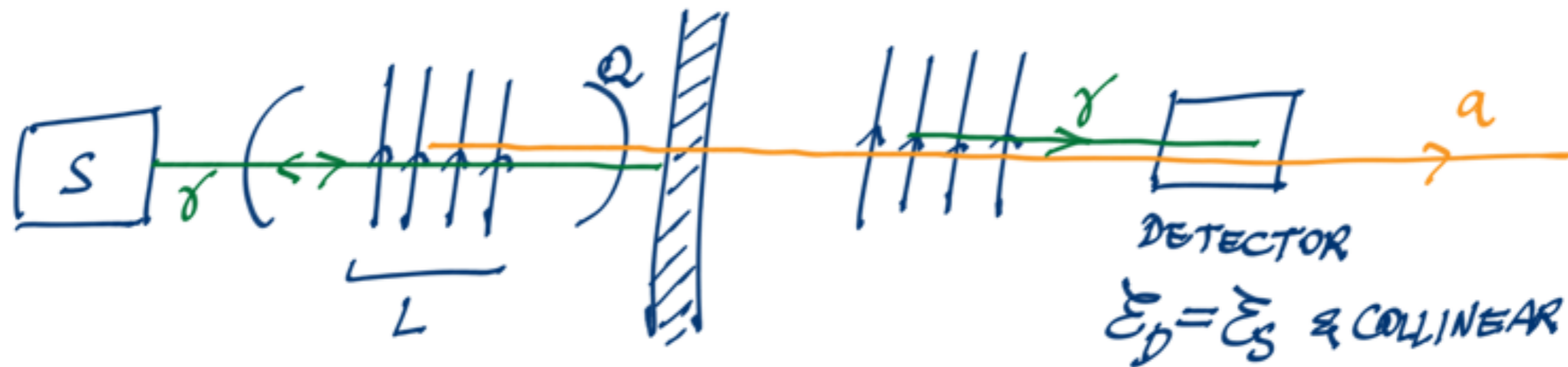
AXION- γ COUPLING

$$G_{a\gamma\gamma} \approx \frac{1}{f} \frac{\alpha}{2\pi} = \frac{m_a}{m_\pi f_\pi} \frac{\alpha}{2\pi}$$

$$T(\pi^0 \rightarrow 2\gamma) = - \frac{1}{f_\pi} \frac{\alpha}{2\pi} \langle \kappa_1 \epsilon_1 \kappa_2 \epsilon_2 | F \cdot \tilde{F} | \pi^0 \rangle$$

a → *f* *a*

LIGHT - SHINING-THROUGH - WALL



$$\dot{N}_e \propto \dot{N}_\gamma P_{\gamma \rightarrow a} P_{a \rightarrow \gamma}$$

$$\propto \dot{N}_\gamma (G \cdot H \cdot L)^4 \quad \text{where } G \sim 1/f$$

with $G \lesssim 10^{-10} \text{ GeV}^{-1}$

$$(GHL)^4 \lesssim 10^{-35}$$

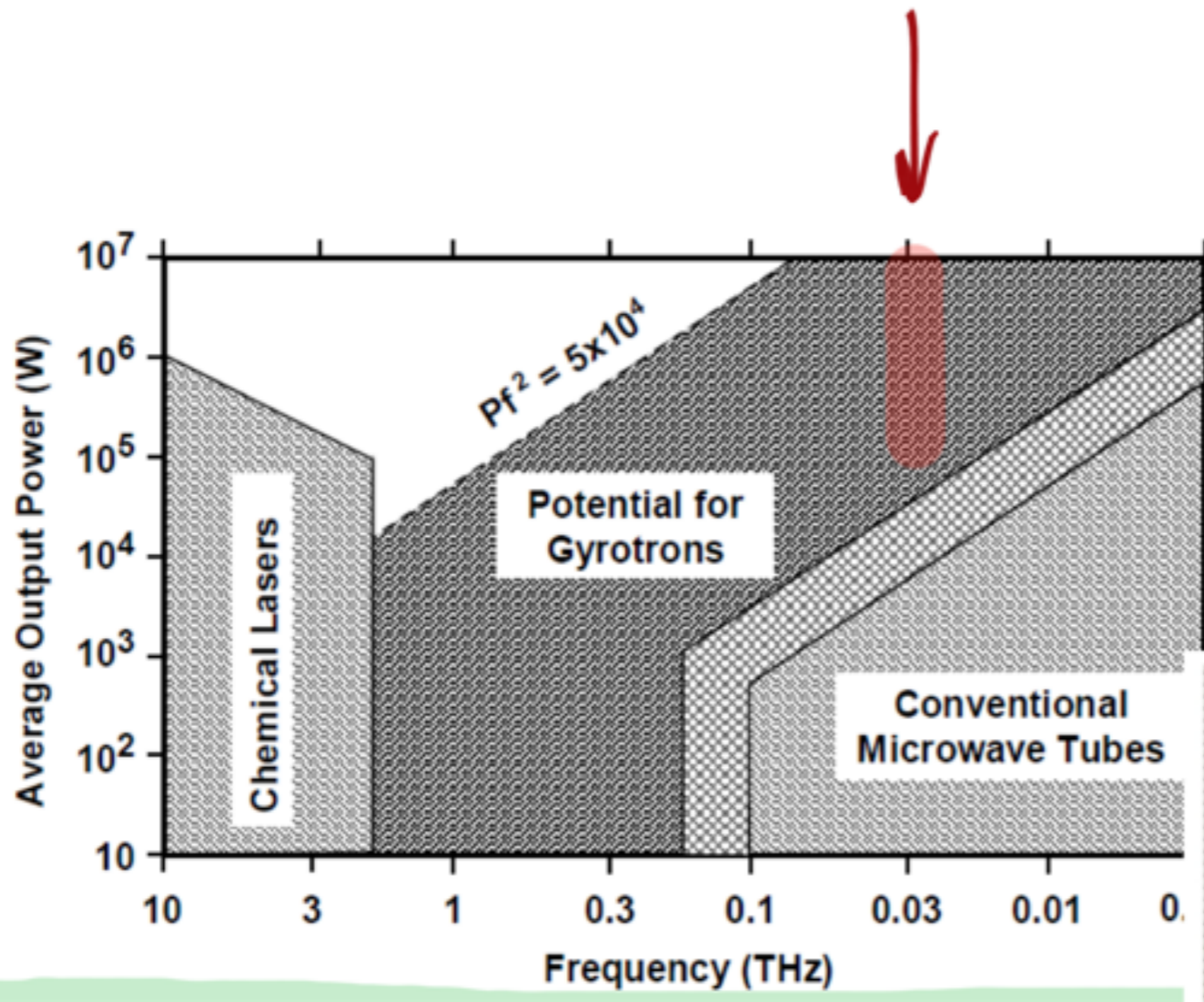
MEGAWATT CYCLOTRON SOURCES can produce (@30GHz)

$$\dot{N}_\gamma \approx 10^{28} / \text{sec}$$

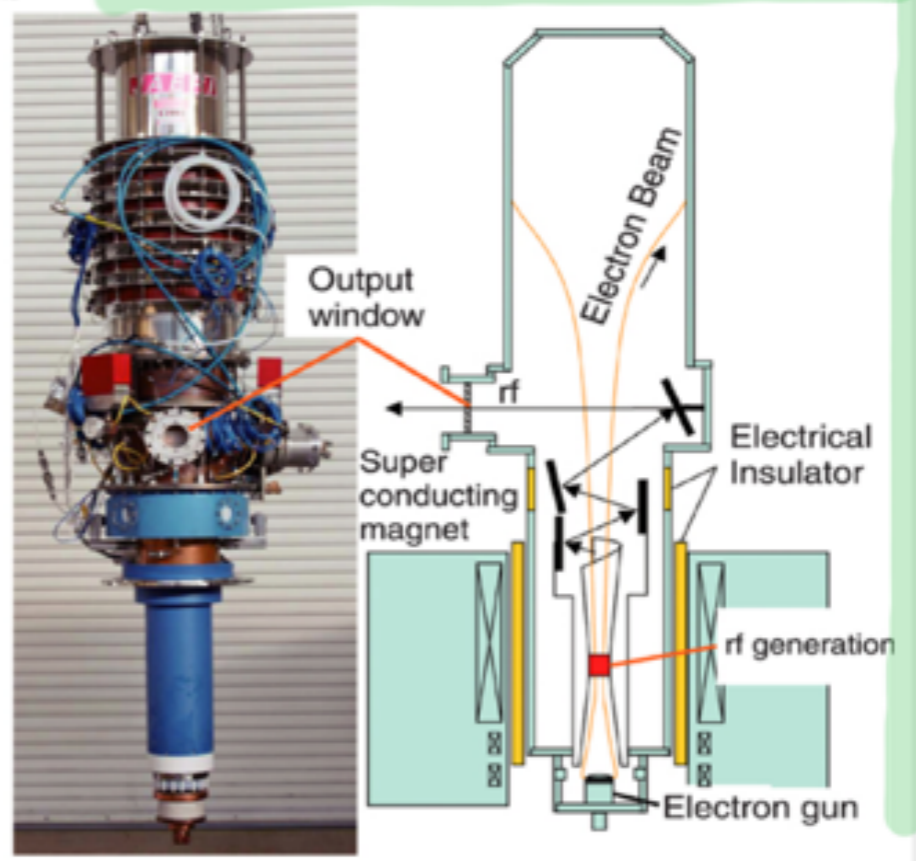
w/ continuous emission.

$$(10 \text{ LSW events/yr}) \times Q$$

Gyrotrons



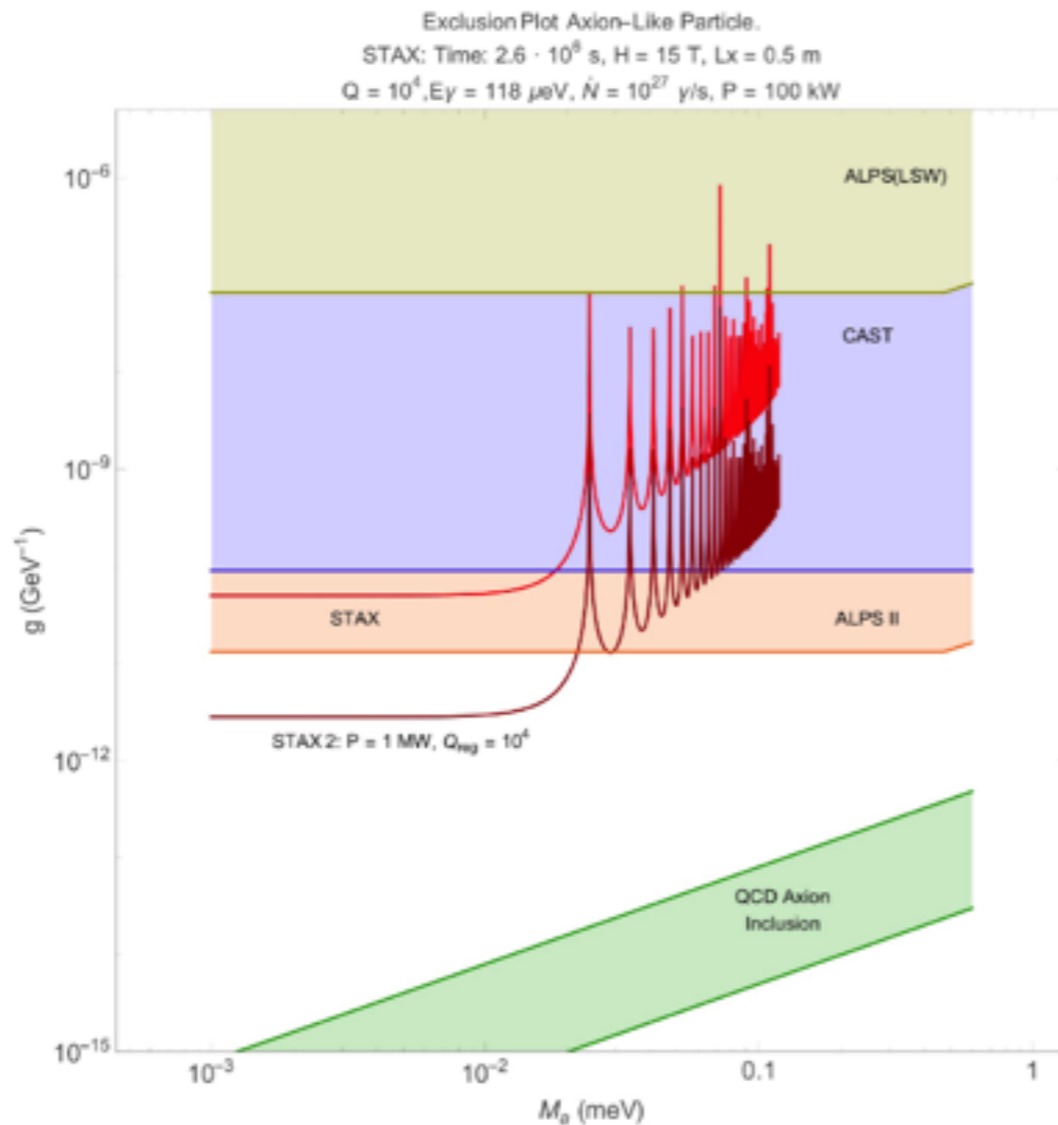
CW highly desired.



POTENTIAL REACH

$$P = \frac{G^2 H^2 \sin^2(qL/2)}{q^2} \frac{\tilde{\epsilon}_\gamma}{1/L + \sqrt{\tilde{\epsilon}_\gamma^2 - m_a^2}}$$

$$q = \tilde{\epsilon}_\gamma - \sqrt{\tilde{\epsilon}_\gamma^2 - m_a^2} - 1/2L$$



EXCLUSION @ 90% CL

IN CASE OF A NULL RESULT
FOR AXIONS

$$m_a \lesssim 0.02 \text{ meV}$$

ONE MONTH EXPOSURE
AND ZERO DARK COUNTS

STAX @ 100 KW
STAX2 @ 1 MW
+ REG. R.

L. CAPPARELLI et al.
PHYS. DARK. UNIV. 12 (2016) 37

FABRY-PEROT CAVITIES

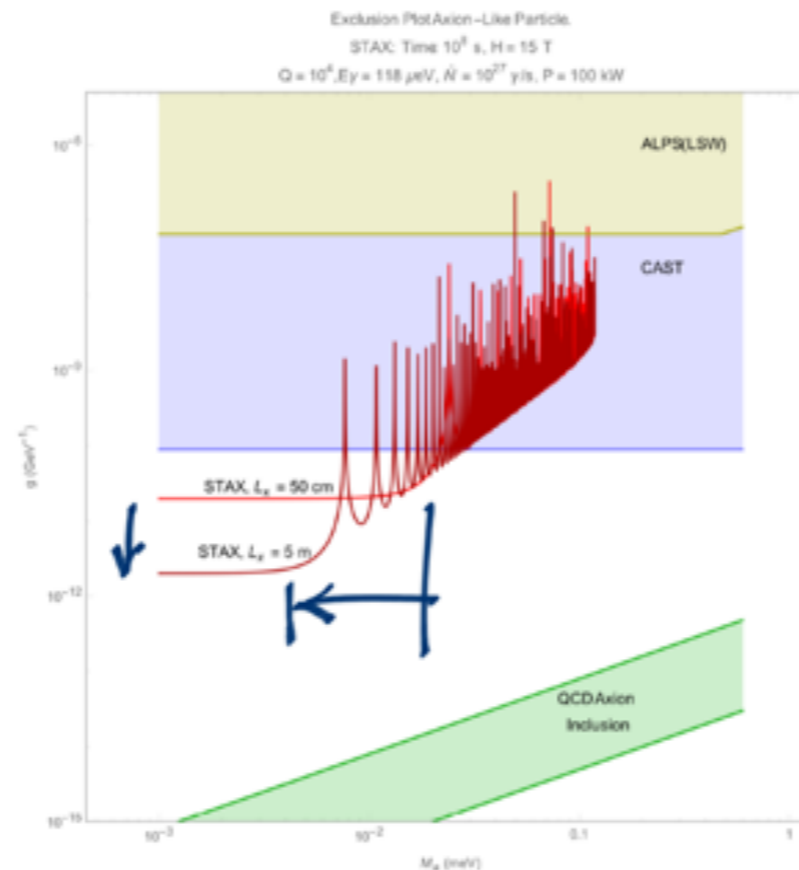
$$P \sim (QH)^4 \cdot L^2 \cdot L^2$$

$$\downarrow$$
$$QL^2 \quad (Q \sim 10^5 \text{ in MW})$$

THIS ALLOWS TO EXPLORE Q VALUES SMALLER BY $Q^{-1/4}$

Someone suggests $Q^{-1/2}$ by setting a 'regeneration' cavity.

MAKING L LONGER MEANS THAT THE ONSET OF OSCILLATIONS
SHIFTS TO SMALLER VALUES BY $1/\sqrt{x}$ IF $L \rightarrow xL$



Some Numbers

Improvements are possible w/ FP cavities



very high Q for mw. $\sim 10^4 \div 10^5$

Parameter	ALPS	STAX	gALPS / gSTAX	STAX II	gALPS / gSTAXII
Laser Power	0.8 W	100 kW	18.8	1 MW	188
Photon Energy	2.327 eV	124 μ eV	11.7	124 μ eV	11.7
Cavity Q-factor	55.0	10^4	3.7	10^8	37
H * L _x	22 T m	7.5 T m	0.3	7.5 T m	0.3
Detection Efficiency	0.9	1.0	1.0	1.0	1.0
Detector Noise	$1.8 \cdot 10^{-3} \text{ sec}^{-1}$	10^{-9} sec^{-1}	34.0	10^{-9} sec^{-1}	34
Combined Improvement			$\sim 10^4$		$\sim 8 \cdot 10^5$

TES

TES work @ T slightly below T_c .

$$V_{\text{TES}} \approx 2 \times 10^{-22} \text{ m}^3 \text{ @ } 10 \text{ mK}$$

$$1\gamma (30 \text{ GHz}) \rightarrow \Delta T_c \approx 40 \text{ mK}$$

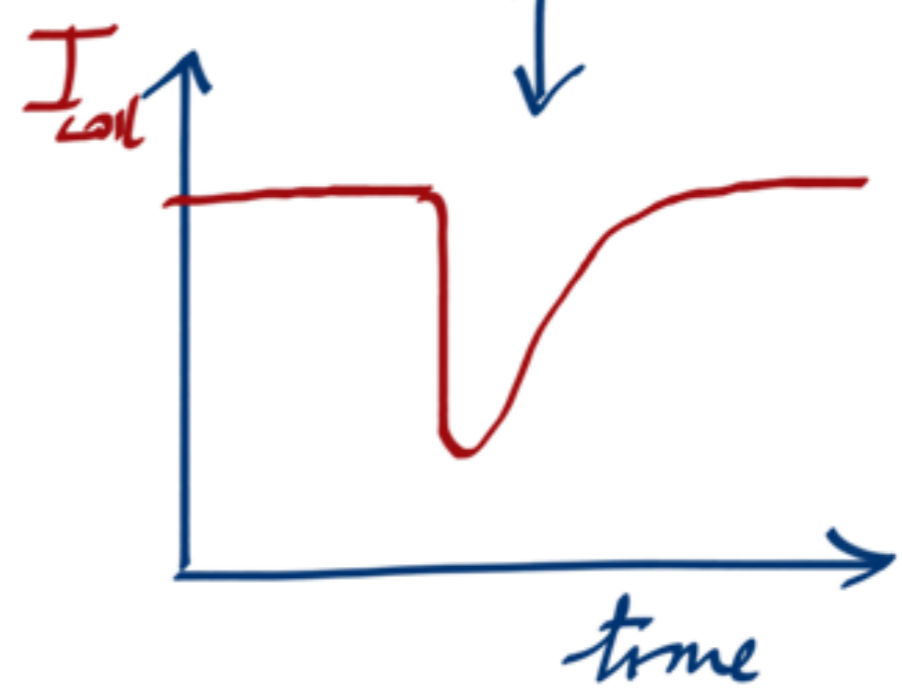
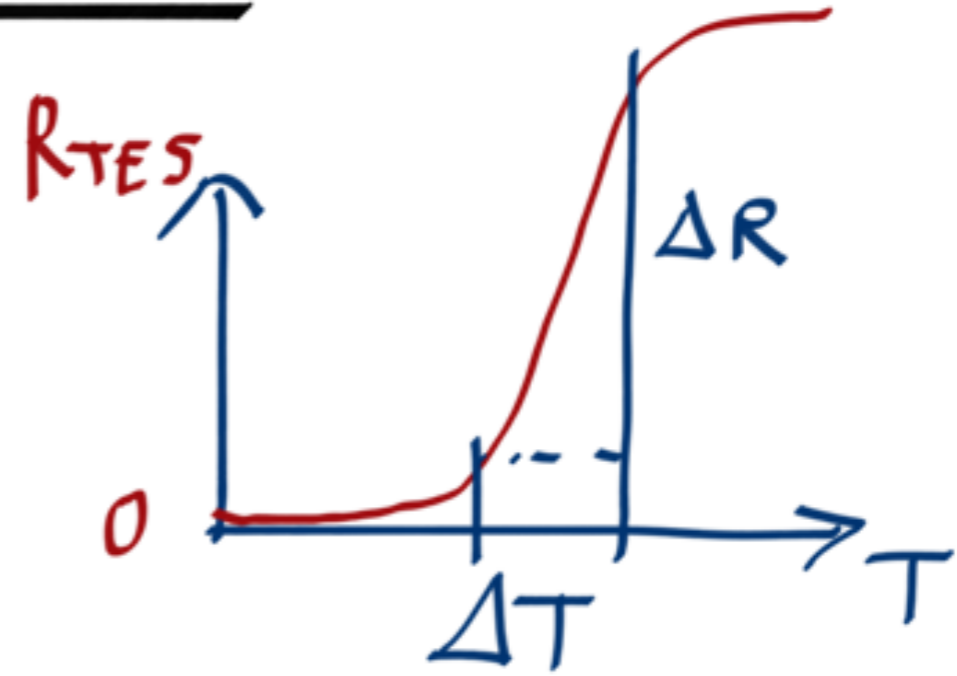
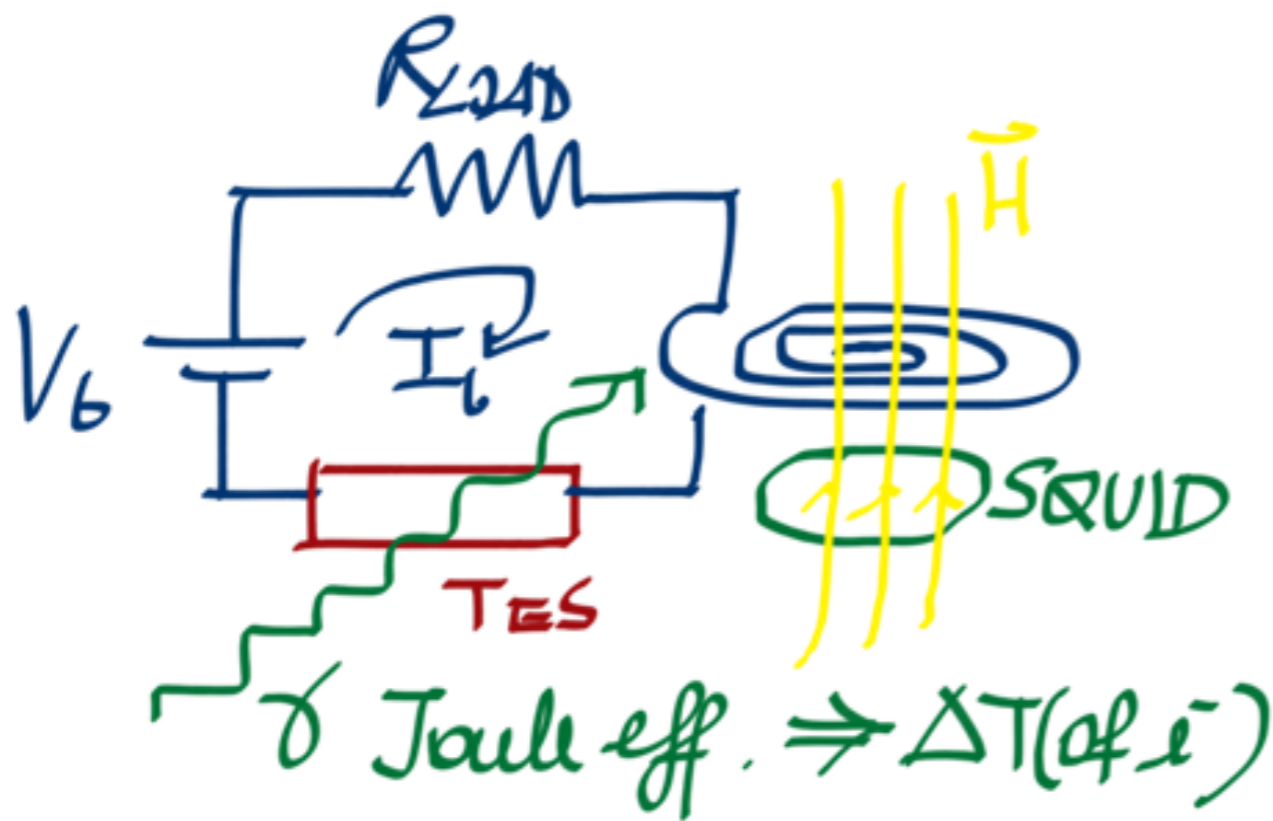
Estimate ϵ engineer ΔI -

— SQUID SPECTRAL NOISE DENSITY

$$\frac{1 \text{ pA}}{\sqrt{\text{Hz}}}$$

— to be multiplied by the det. passband^{1/2}
 $\approx \sqrt{100 \text{ Hz}}$

EYE SCHEME



$\tau(\epsilon - \phi @ 10 mK) \approx 0.1 sec$

Read a voltage on SQUID

R&D on $\Delta T, \Delta R, \Delta V_{SQUID}$ @ 30 GHz & 10 mK.

Oscillations

Occur when $qL \ll 1$ fails -

$$q \sim \frac{m_a^2}{2E_\gamma} \longrightarrow \frac{(m_a - m_\gamma^*)^2}{2E_\gamma}$$

Shifts the onset of oscillations to higher m_a values.

Example (CAST)

Introduce He gas in the cavity, δ will have an effective velocity $c/n(\omega) = |\vec{k}|/E_\gamma$

$\Rightarrow m_\gamma^* > 0$. N.B. CAST uses X-rays.

WIMPS & CNTs (DECANT)

LM CAPPARELLI (UCLA)

G CAVOTO (INFN ROMA)

F COCINA (SAPIENZA)

J FERRETTI (INFN ROMA)

D MAZZILLI (SAPIENZA)

A DP (SAPIENZA)

AXIONS & SUB-THE γ s (STAX)

LM CAPPARELLI (UCLA)

G CAVOTO (INFN ROMA)

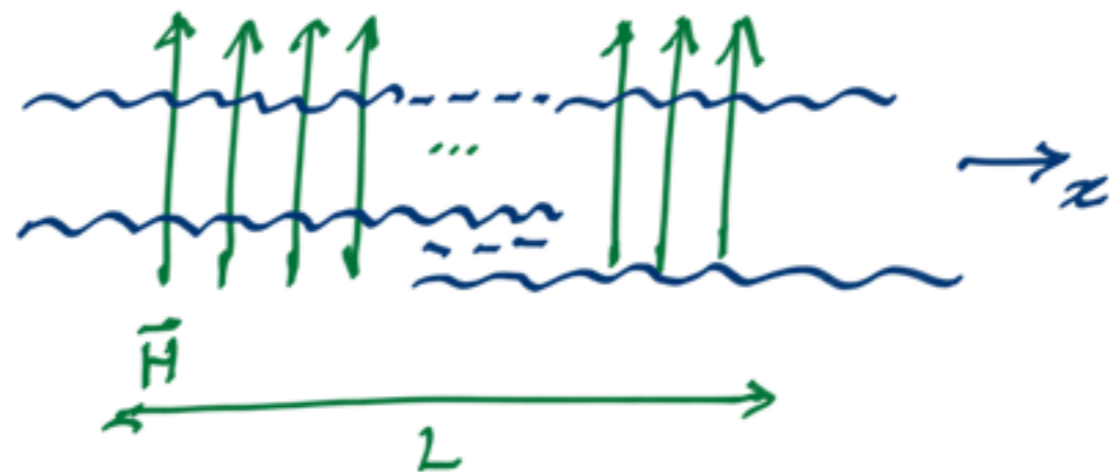
J FERRETTI (INFN ROMA)

F GAZOTTO (SNS & NEST)

A DP (SAPIENZA)

P SPAGNOLO (INFN PISA)

APPENDIX



$$\Sigma \sim G^2 H^2 E_f^2 \int dq \frac{\sin^2(qL/2)}{q^2(p^2 - m_a^2 + i\epsilon)}$$

$$(p^2 - m_a^2 + i\epsilon) = -(q - (q_1 + i\epsilon))(q - (q_2 - i\epsilon))$$

$$q_1 = E_f + p^*$$

$$i\epsilon \leftarrow i\epsilon p^* - \epsilon^2$$

$$q_2 = E_f - p^*$$

$$p^* = \sqrt{E_f^2 - m_a^2} > 0$$

Do integral in the complex plane, take its 'im' part and get the standard formula

APPENDIX

$$P = G^2 H^2 \frac{E_y}{\sqrt{E_y^2 - m_a^2}} \left(\frac{\sin^2(q_2 L/2)}{q_2^2} + (2 \rightarrow 1) \right)$$

$$\lambda_a < \frac{L}{2} \Rightarrow |q| > \frac{1}{2L}$$

FWD a's $q < E_y - \frac{1}{2L}$

BKWD a's $q > E_y + \frac{1}{2L}$

from $p = k - q$

Since $q_1 > q_2$

$$q_2 \lesssim m_a - \frac{1}{2L}$$

$$q_1 \gtrsim m_a + \frac{1}{2L}$$

$$\min(q_1 - q_2) = \frac{1}{L}$$

Going back to the contour integral evaluation we find that this condition translates into an upper-bound for the P

$$P_{\max} = G^2 H^2 \frac{\sin^2(qL/2)}{q^2} \frac{m_a}{1/L}$$