Light dark matter: new detection possibilities

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OUTLINE

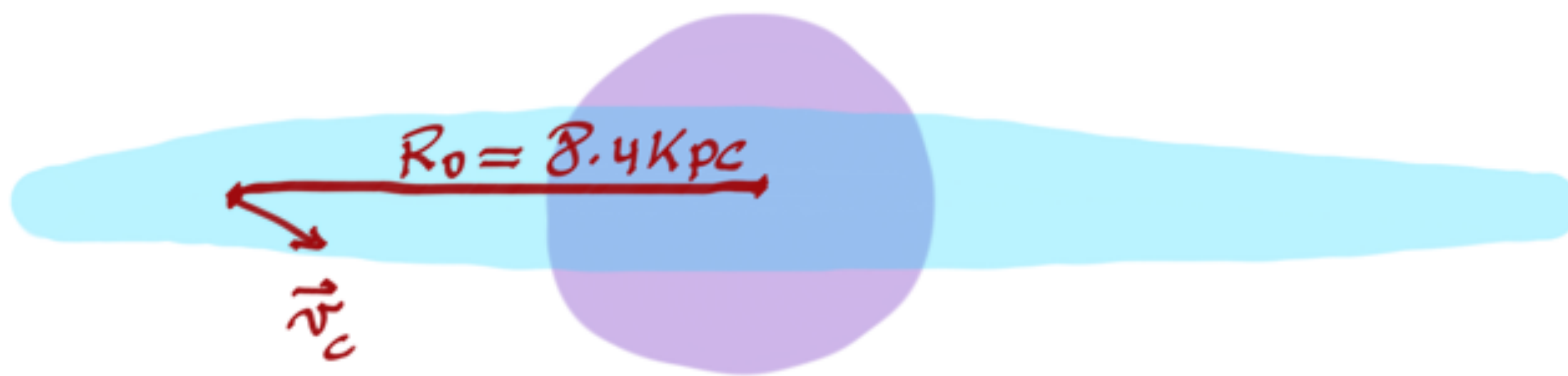
I - DARK MATTER HALO AND WIMP WIND

II - CARBON NANOTUBES AS DIRECTIONAL DETECTORS

III - AXION-LIKE PARTICLES

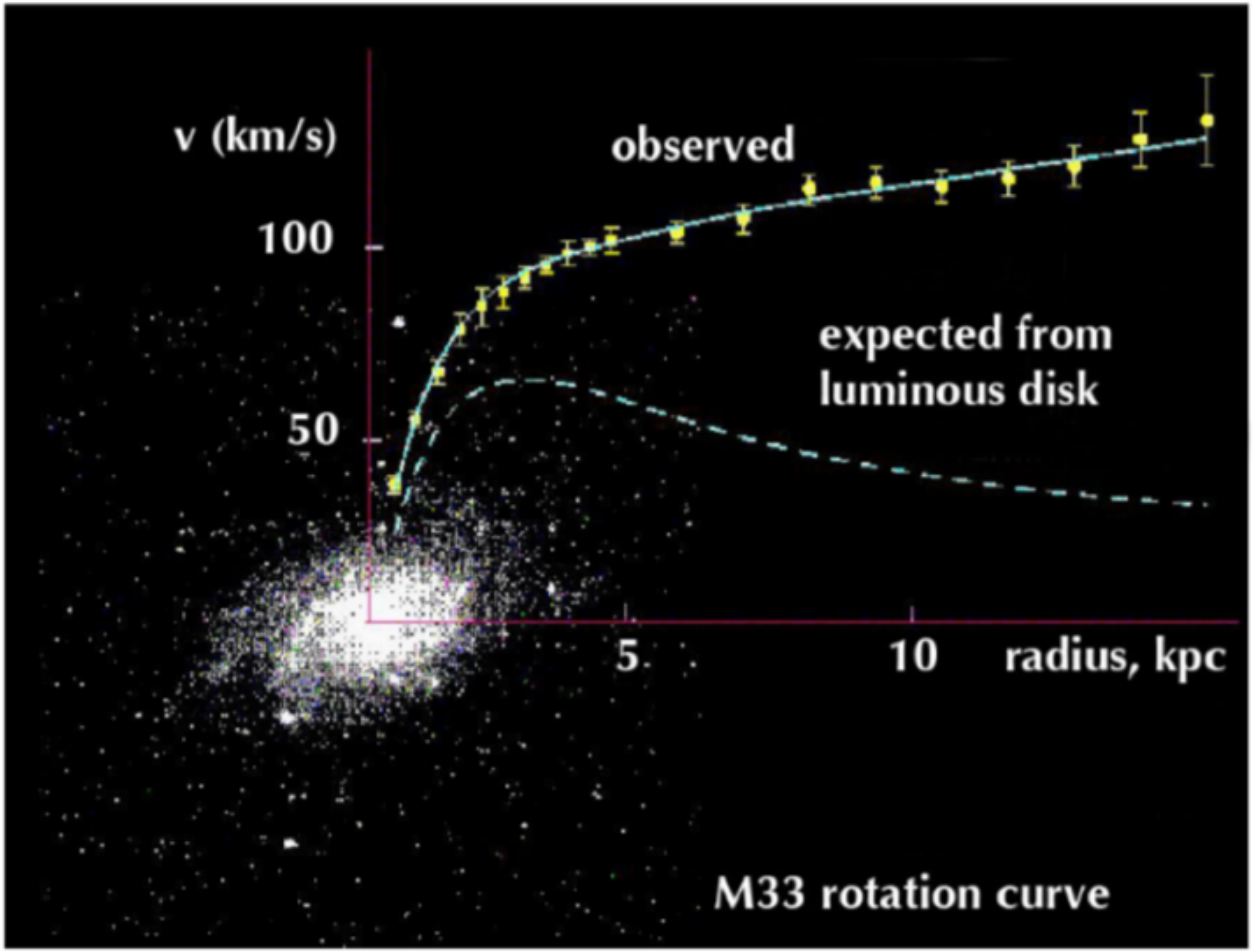
IV - LIGHT SHINING THROUGH WALL
WITH SUB-THz PHOTONS

DM halo



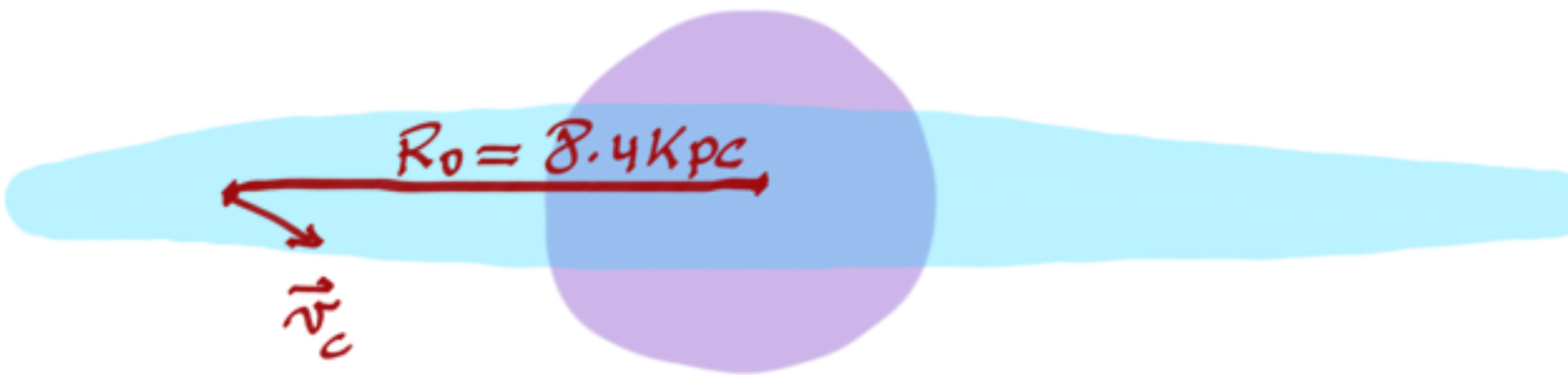
$$\frac{G M(r)}{r^2} = \frac{v_c^2(r)}{r}$$

(Velocity of the Local Standard of Rest)



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

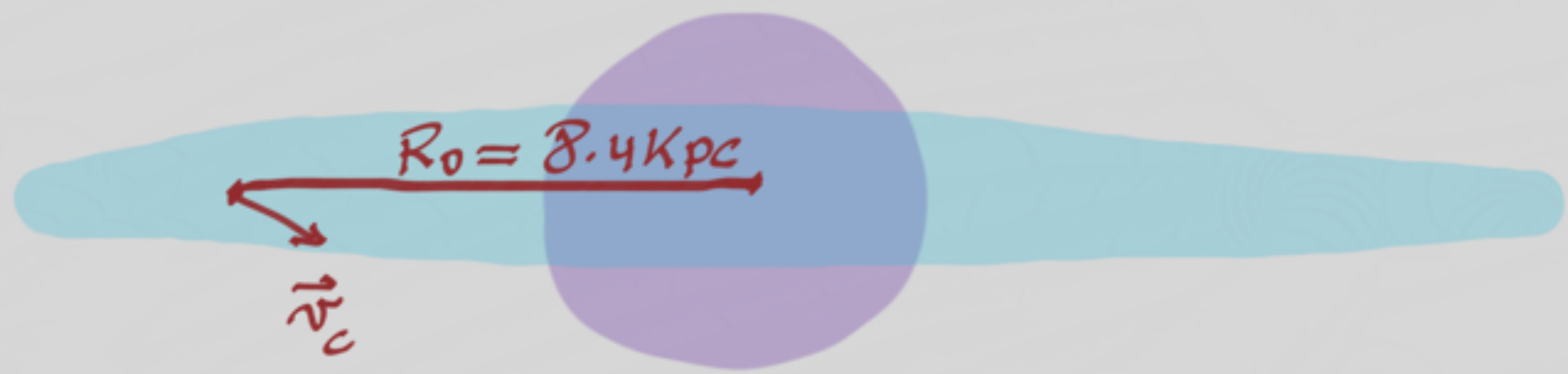
DM halo



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

out of the edge of the luminous disk

DM halo



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

$$\vec{v}_c = (0, 235, 0)\ \mathrm{Km/s}$$

$$\boxed{M_{DM}(R_0) \simeq \frac{1}{2} M_{DISK}}$$

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 $C[f] = 0$).

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

$$v_0 \sim v_{c,\infty} \simeq 235\ \mathrm{Km/s}$$

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

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

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

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

$$v_{esc} \simeq 498 \div 608\ \mathrm{km/s}$$ ("from high velocity stars")

DM halo

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

* 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} $(= 5 \cdot 10^{-25}\, gr/cm^3)$

Left-over particles

In absence of annihilations

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

let σ be the $\chi\chi$ exothermic annihilation xsect.

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

$t \to +\infty$

where $[\rho v \sigma] = \sec^{-1}$

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

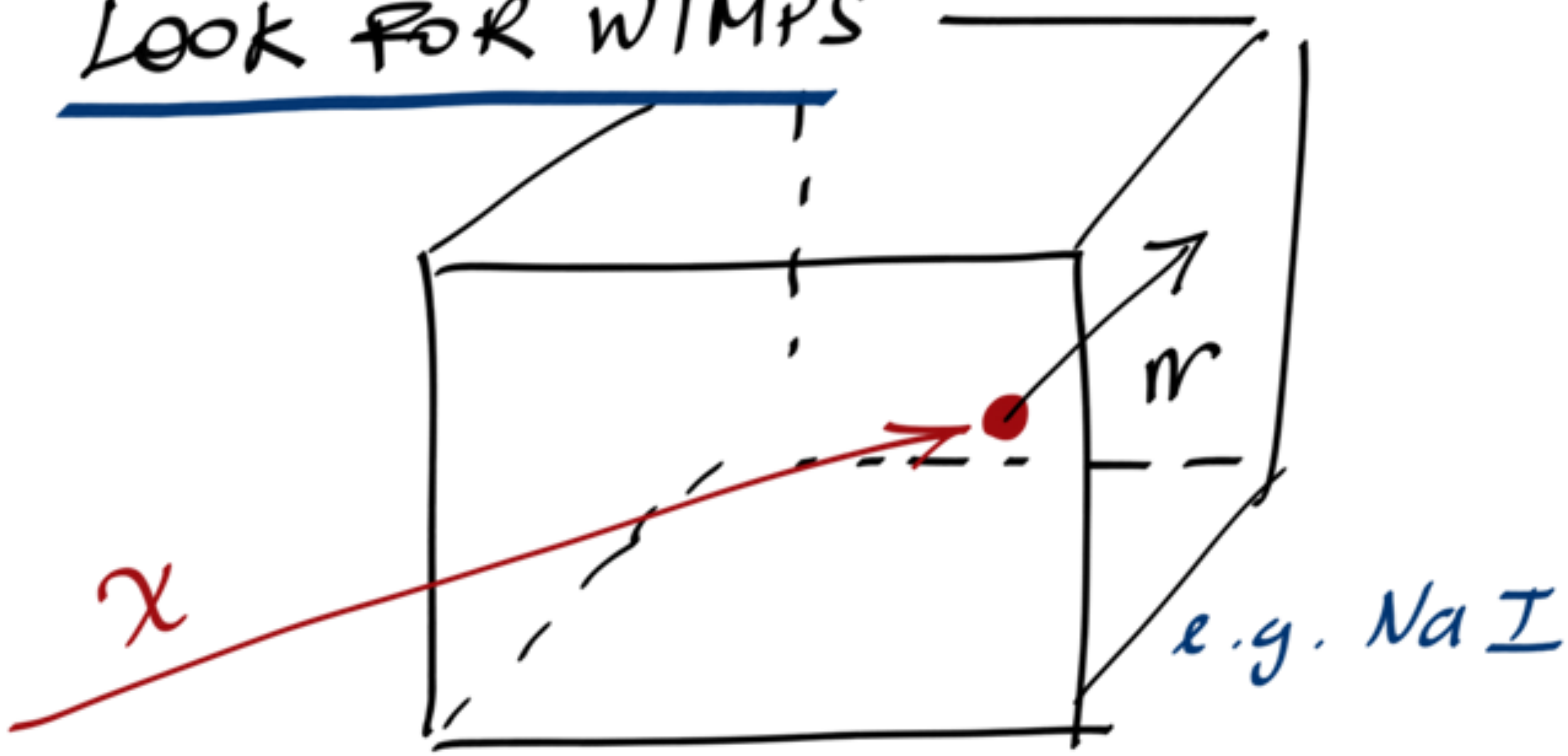
$\left(v\sigma \sim \kappa\, k^{2\ell+1} k'^{2\ell+1}/k^2 \ \& \ k\to 0,\ k'\to \text{const.};\ T\sim a^{-1};\ a\sim t^{2/3};\ \langle , \rangle_{\text{low } T} \sim \int dE\, e^{-E/T} \ldots \right)$

WIMPS

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

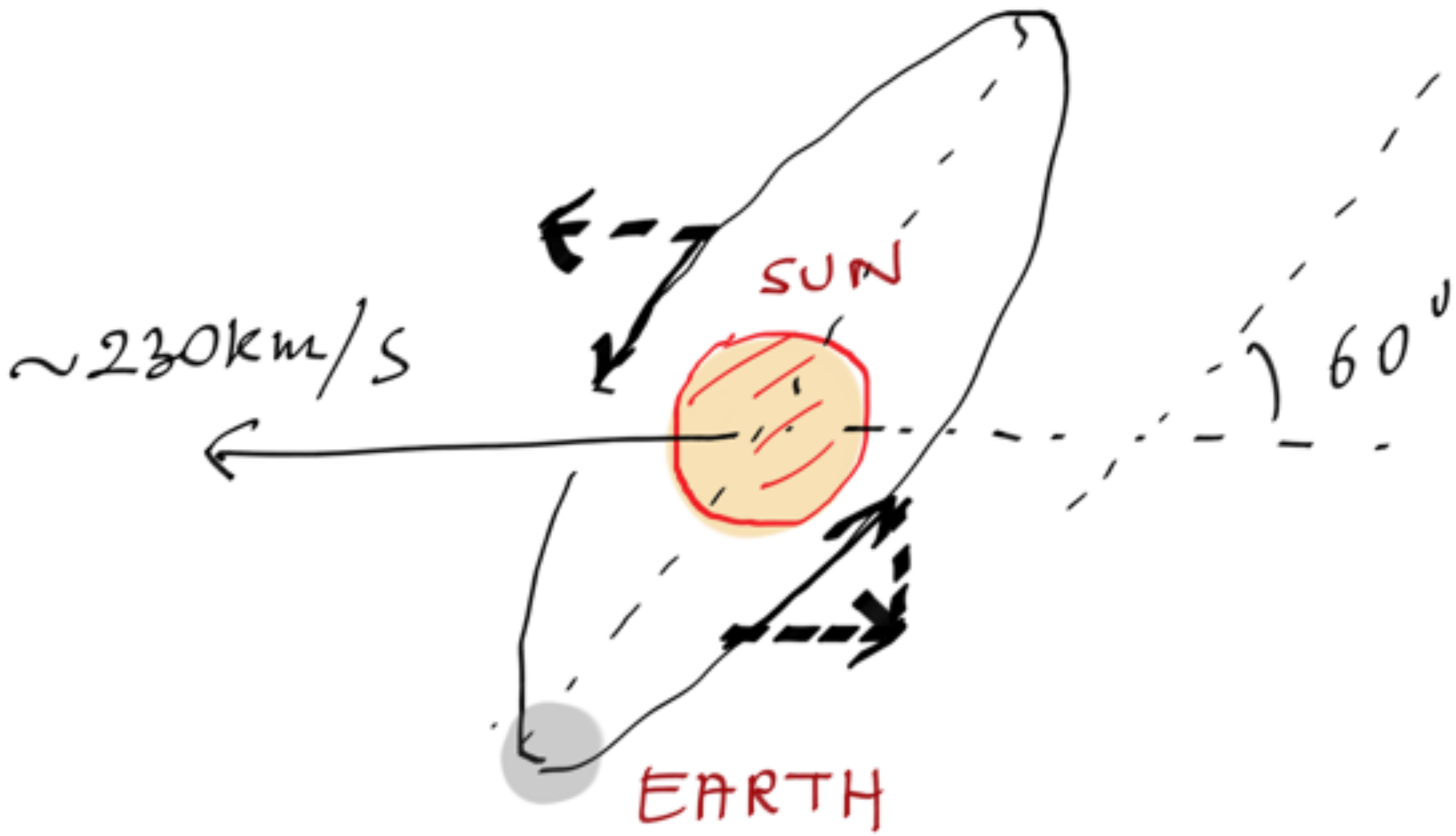
$$\Omega \approx \Omega_{DM}$$

LOOK FOR WIMPS



Crystal.

WIMP WIND



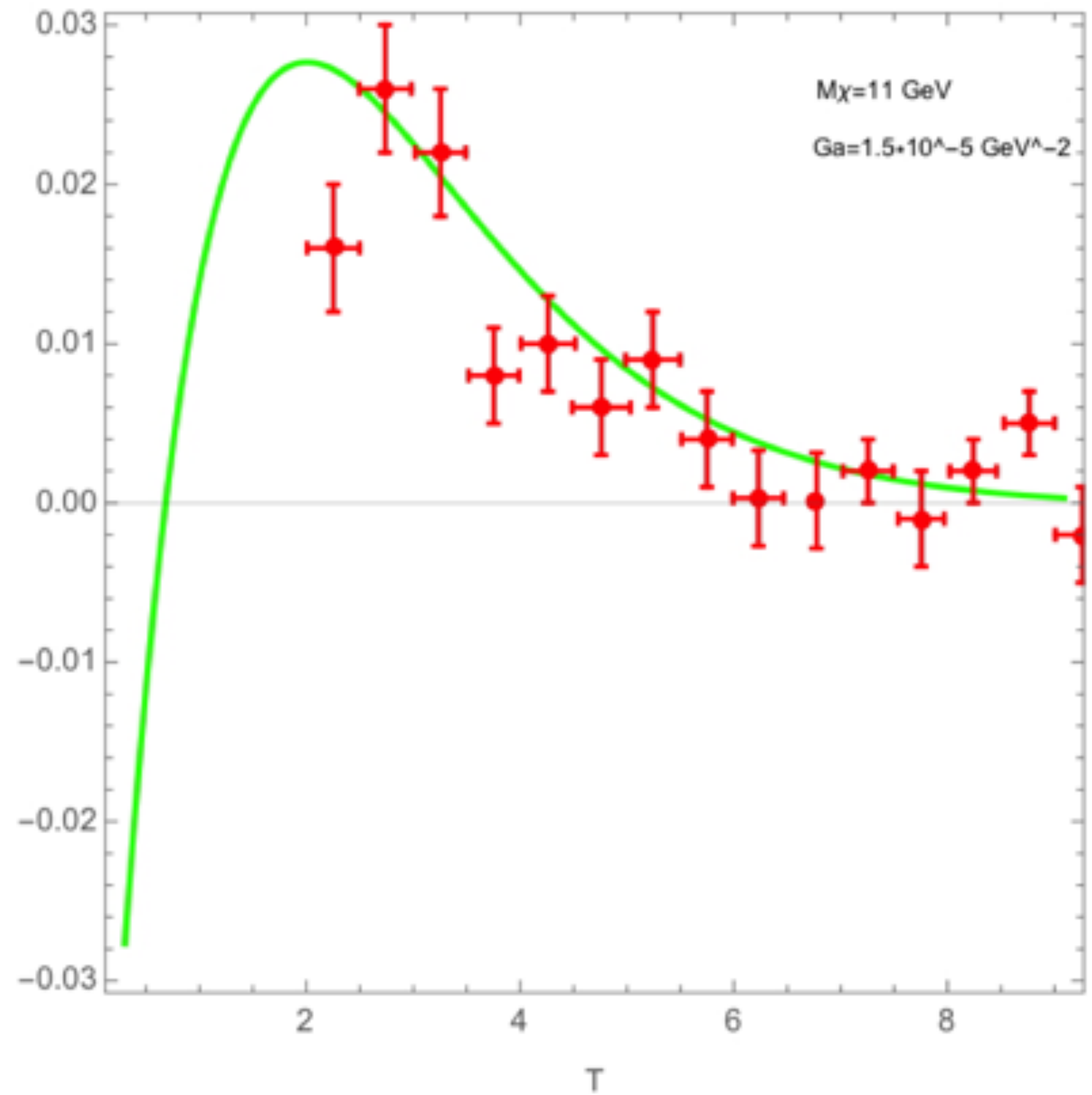
$$\vec{w}(t) = [232 + 15\cos\psi(t)]\,\hat{k}$$

$$\psi(t) = 2\pi\,\frac{t - 152{,}5}{365{,}25} = \omega t + \varphi_0$$

DAMA

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

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



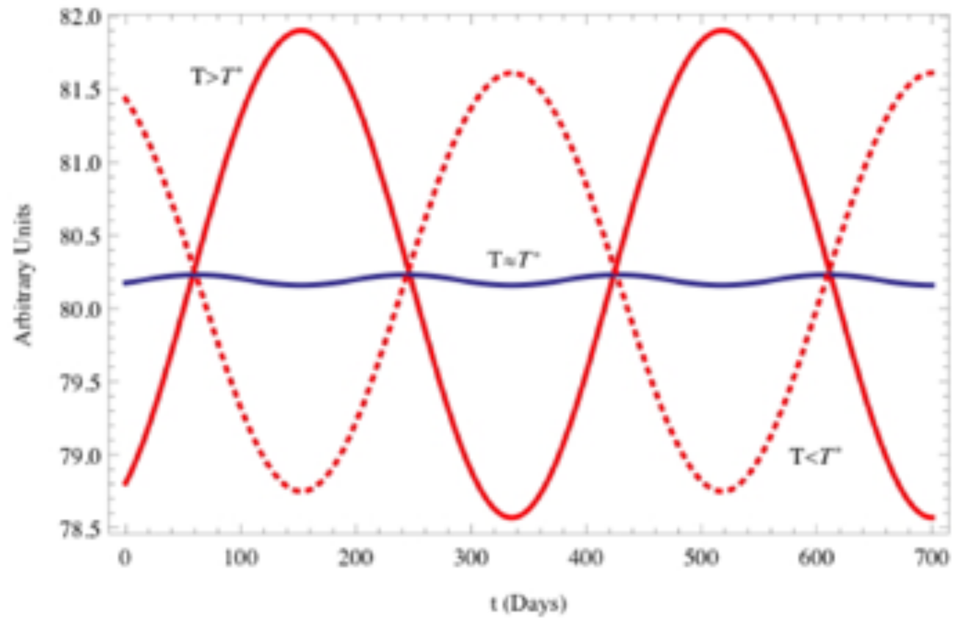
χ - Na in NaI

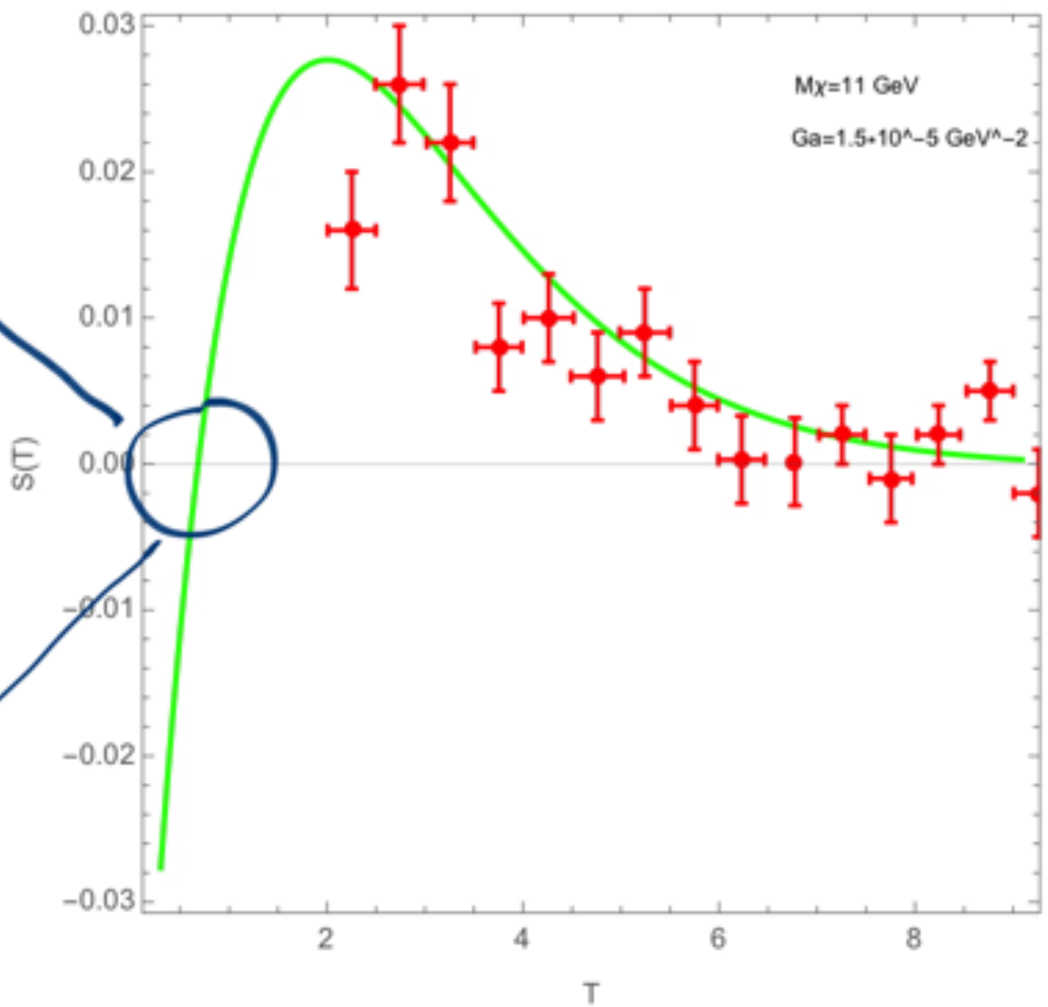
NUCLEAR RECOIL KINETIC ENERGY

(KeVee)

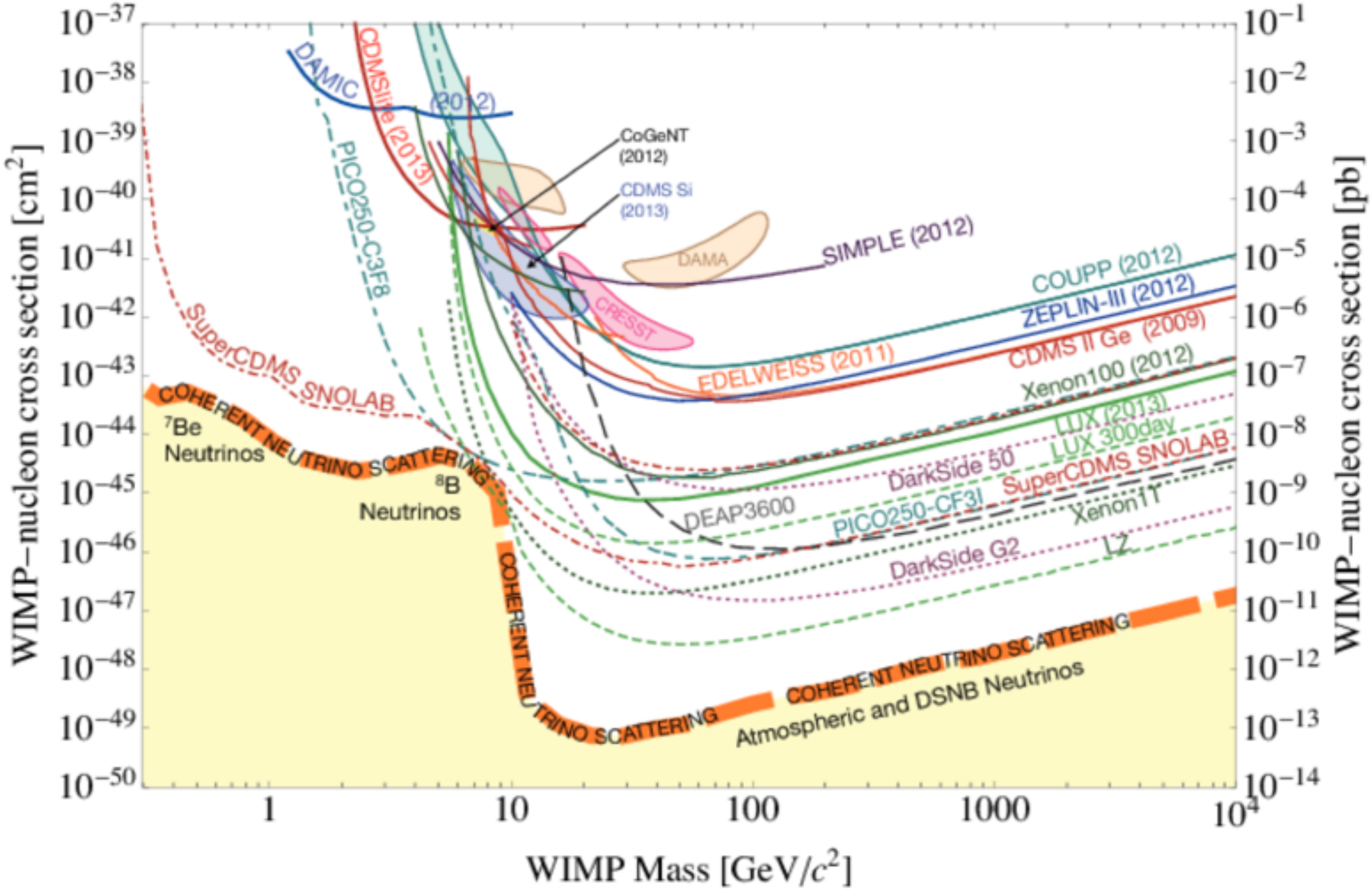
DAMA

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



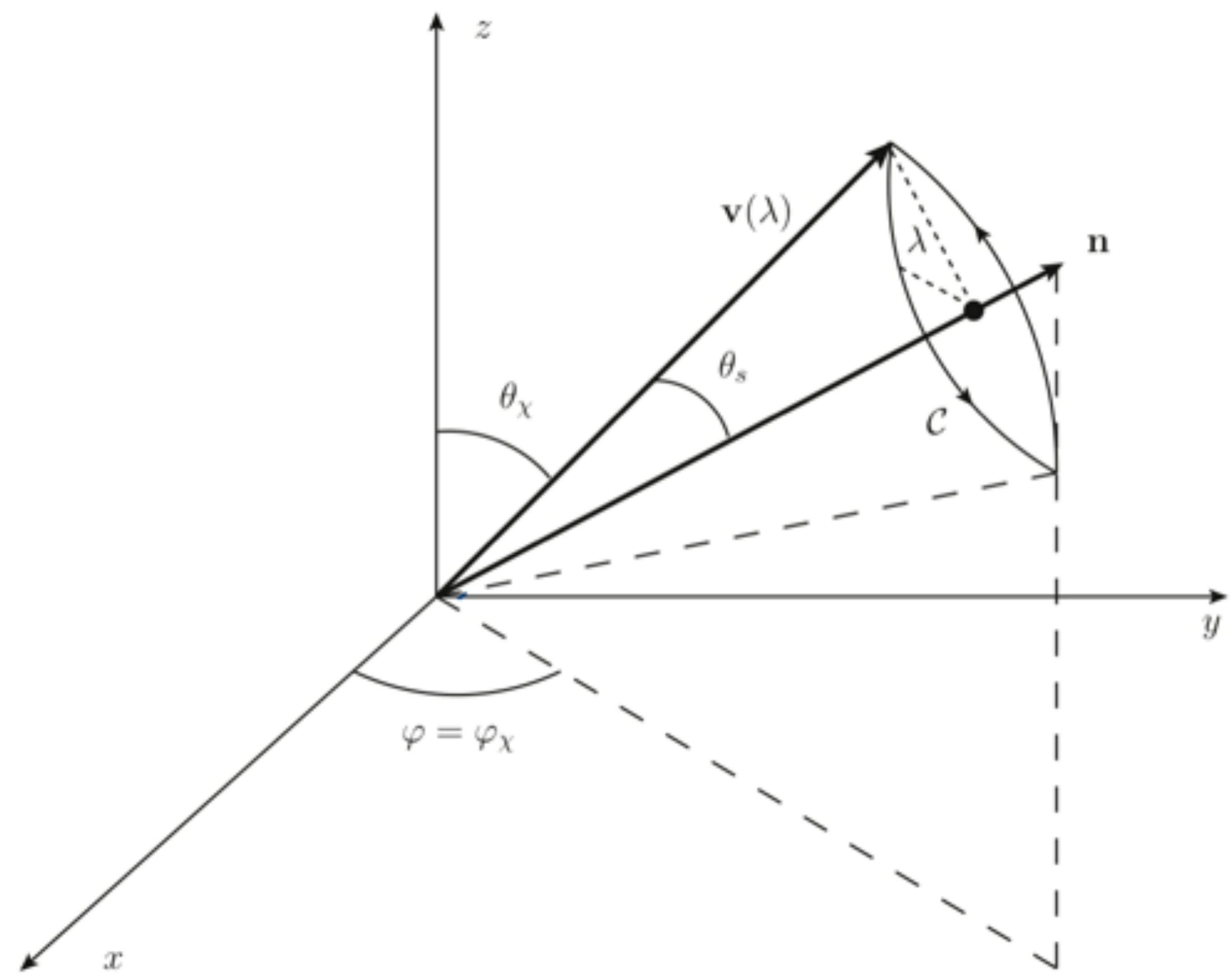


EXCLUSION PLOT



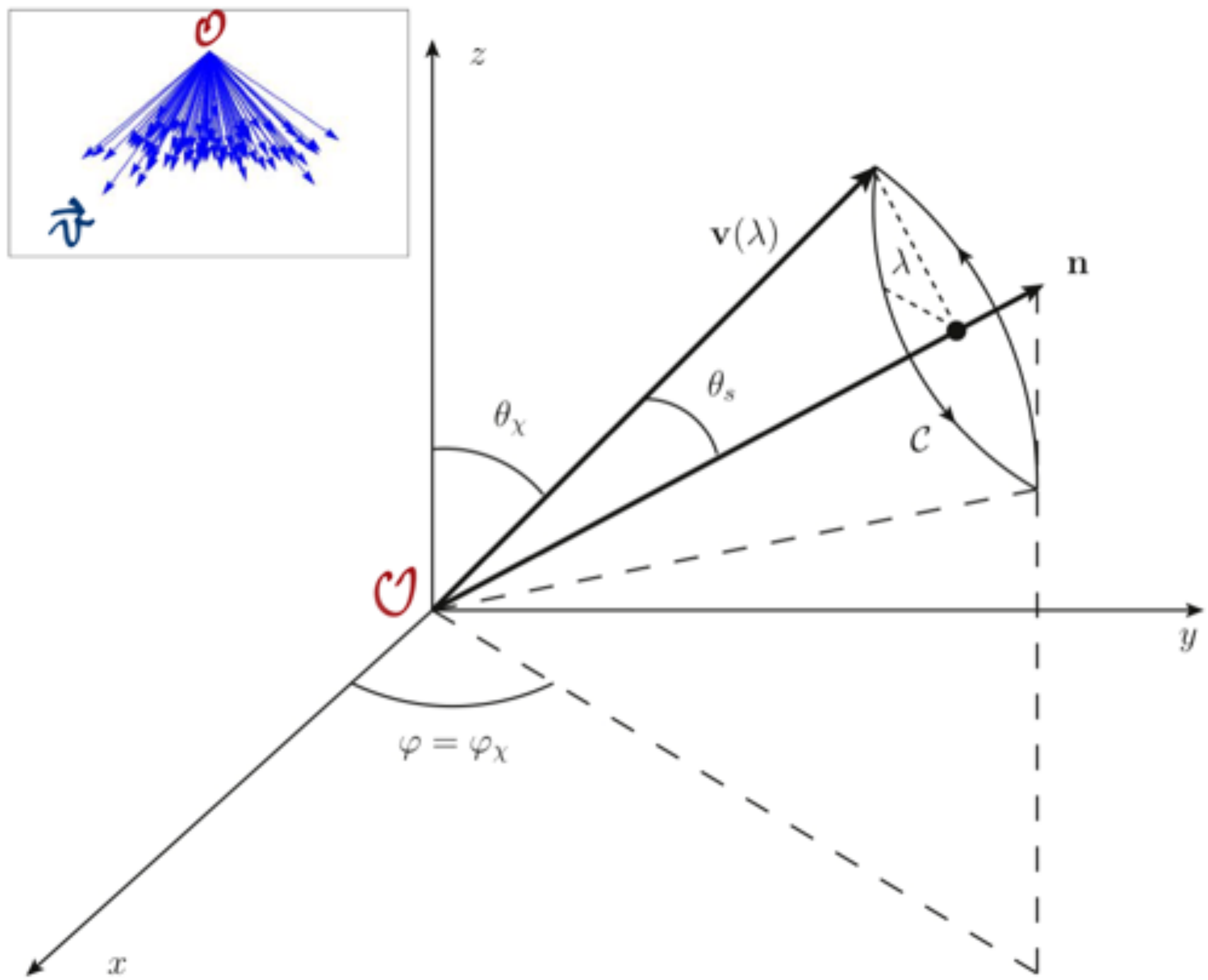
WIMP WIND

★ CYGNUS



WIMP WIND

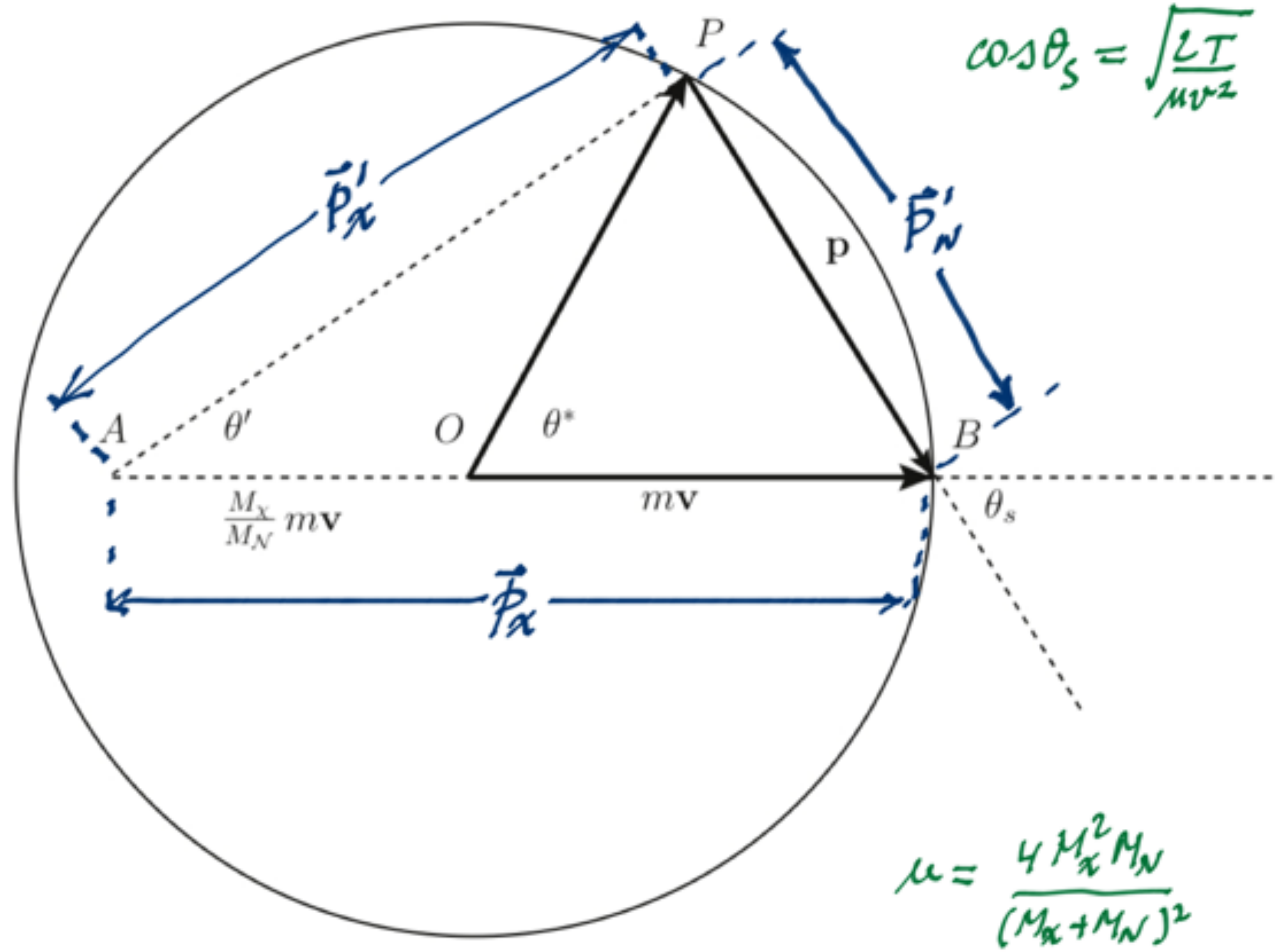
☆ CYGNUS



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

$\theta\ (\equiv \theta_\chi + \theta_s$ if $\lambda = 0) \approx \pi$ is the <u>wind orientation</u>

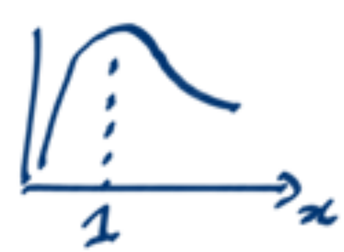
Kinematics



$$\cos\theta_s = \sqrt{\frac{2T}{\mu v^2}}$$

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

$$\frac{(T_N')_{max}}{T_\chi} = \frac{4x}{(1+x)^2}, \quad x = \frac{M_\chi}{M_N},$$



Nuclear Recoils

$$\frac{d\Gamma}{d\Omega_{\hat{n}}} = n_\chi \langle v \frac{d\sigma}{d\Omega_{\hat{n}}} \rangle_{\vec{v}}$$

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

$$\sigma_{\chi p} \simeq 2 \cdot 10^{-4}\, pb$$

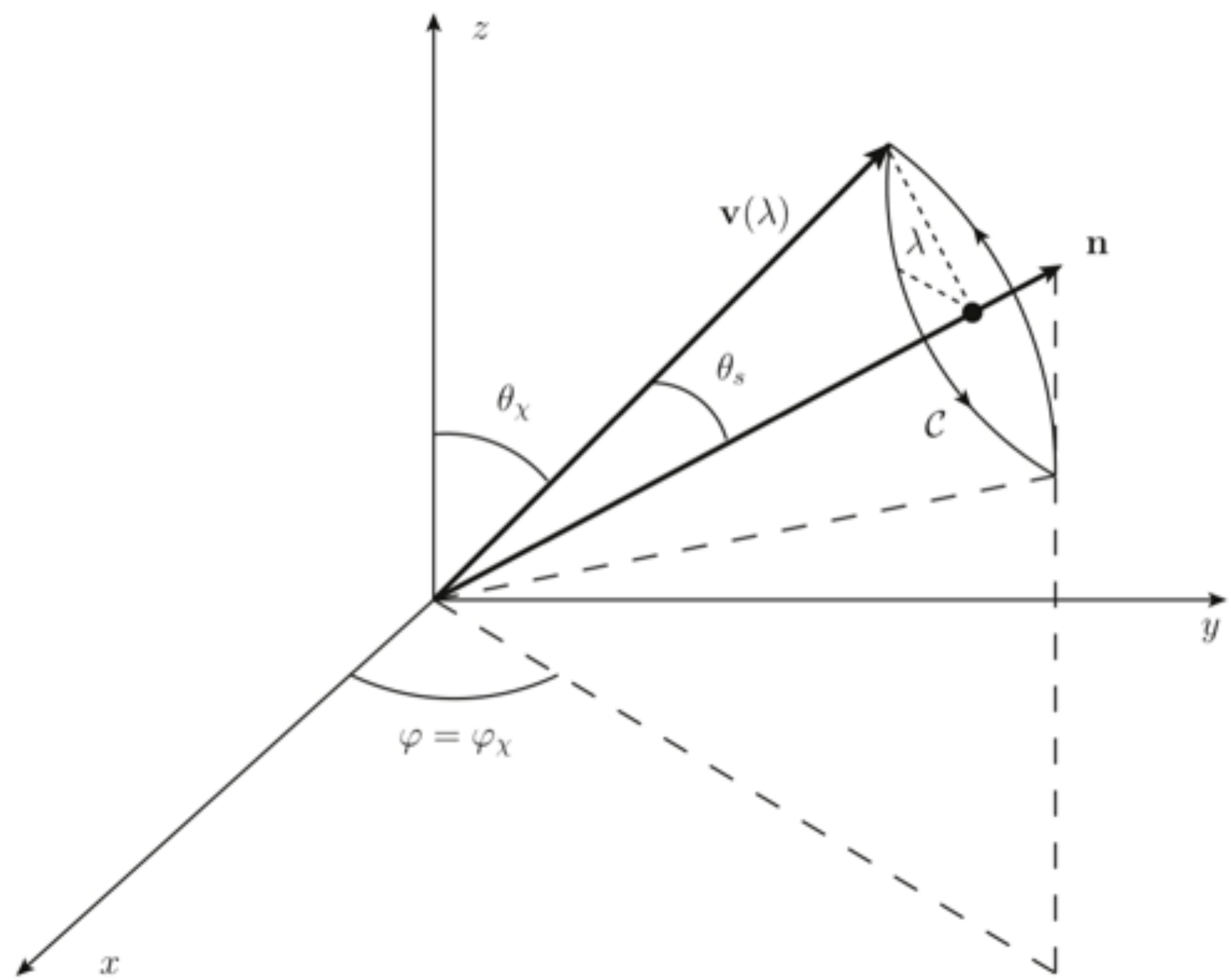
With this we find

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

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

WIMP WIND

CYGNUS



WIMP WIND

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

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

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

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

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

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

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

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

WIMP WIND

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

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

$$B = 2 v w_z(t) \sin\theta_s \sin\theta$$

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

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

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

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

velocities are in units of c

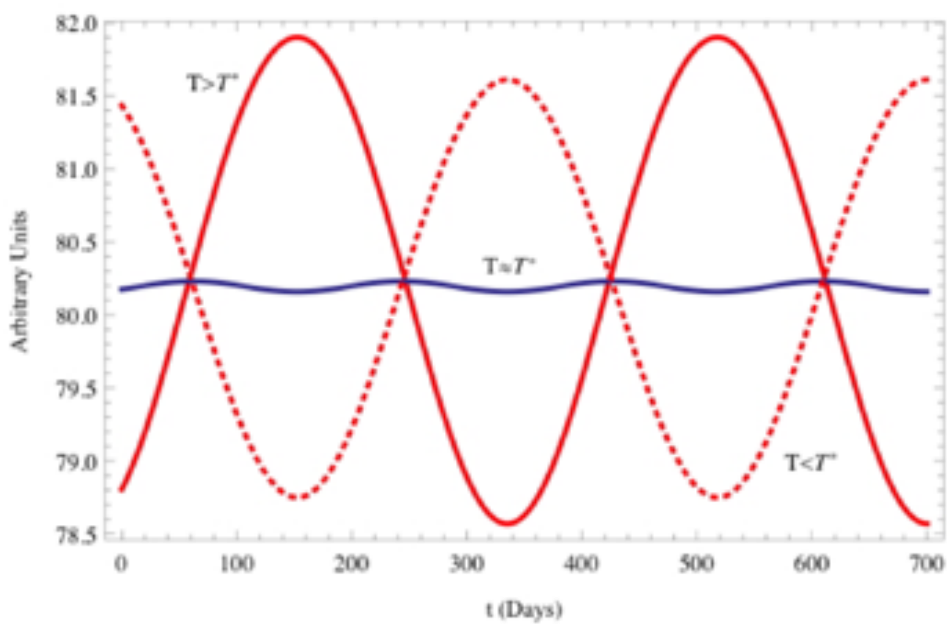
v_{ex} (on $\oplus$) $\simeq 780$ km/s

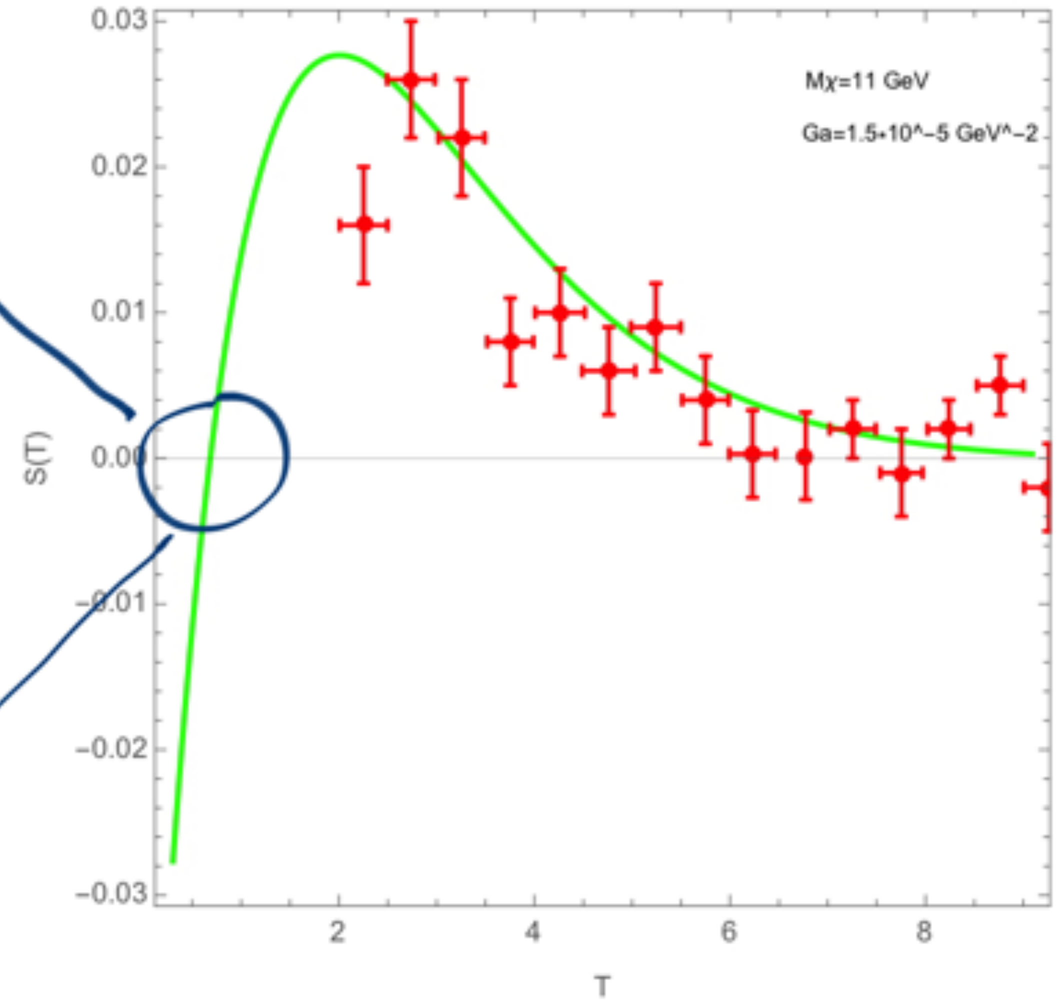
$n_\chi = \rho_\chi / M_\chi = 0.4\,\text{GeV/cm}^3 / 11\,\text{GeV}$

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

DAMA

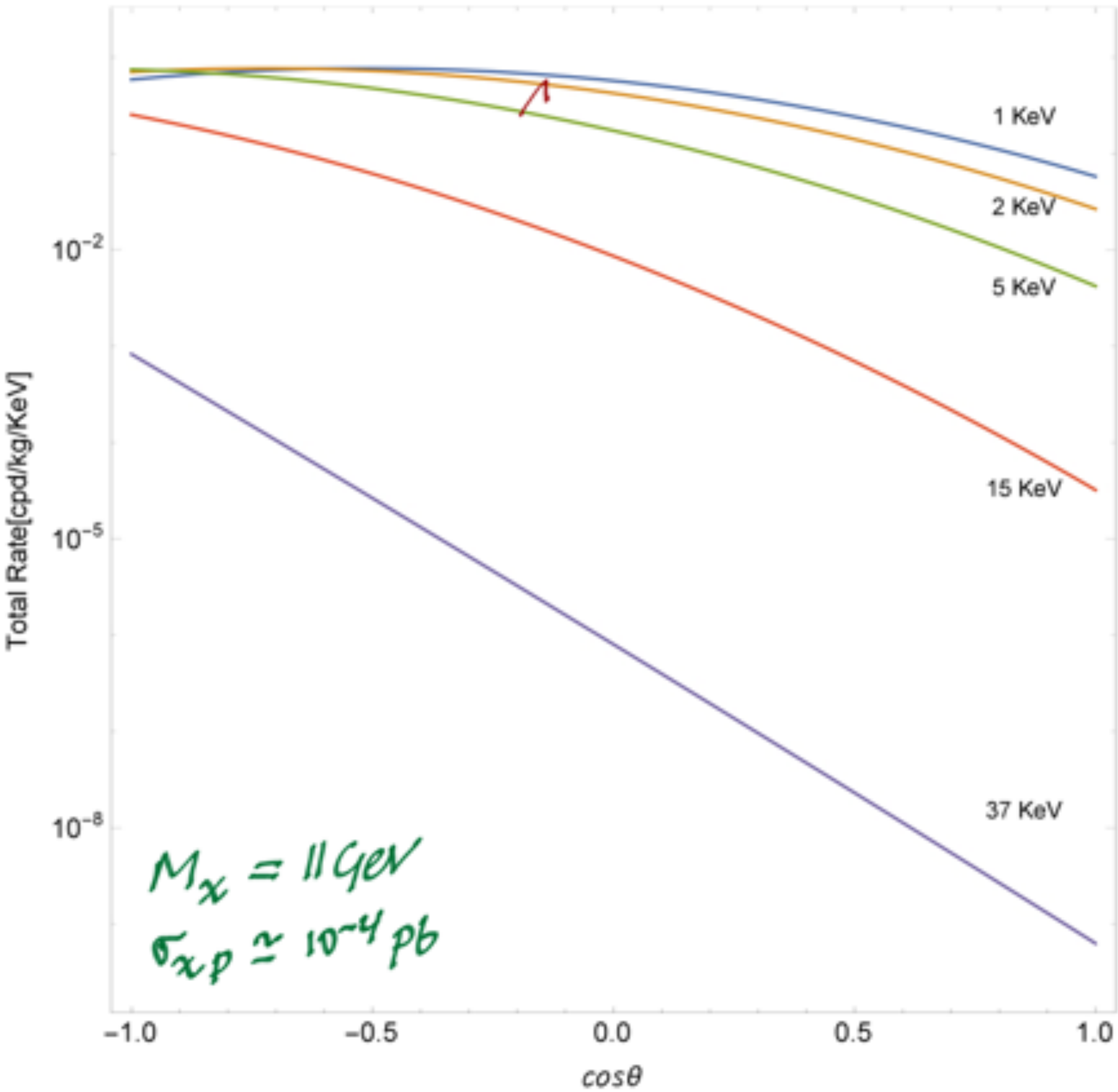
$$\frac{d\Gamma}{dT} = A(T) + S(T)\cos(\omega t + \varphi_0)$$

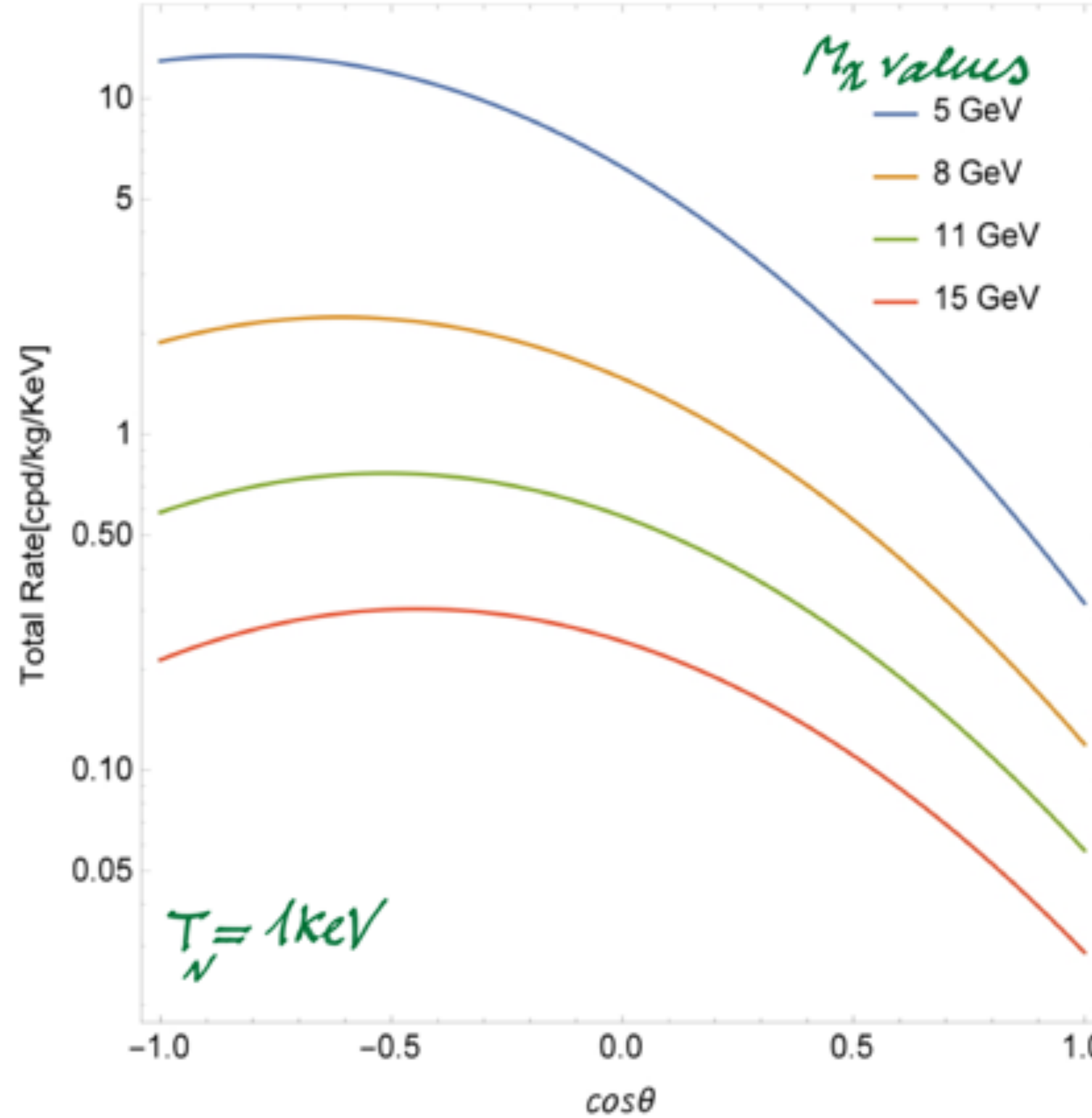


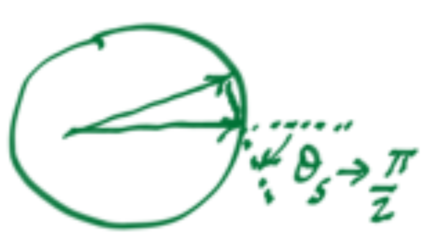


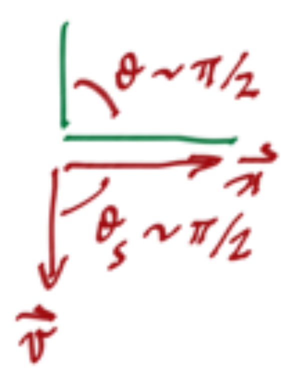
$$\frac{d\Gamma}{dT} = \int d\cos\theta \, \frac{d\Gamma}{dT\, d\cos\theta} \rightarrow \text{Fourier exp.}$$

Nuclear Recoils





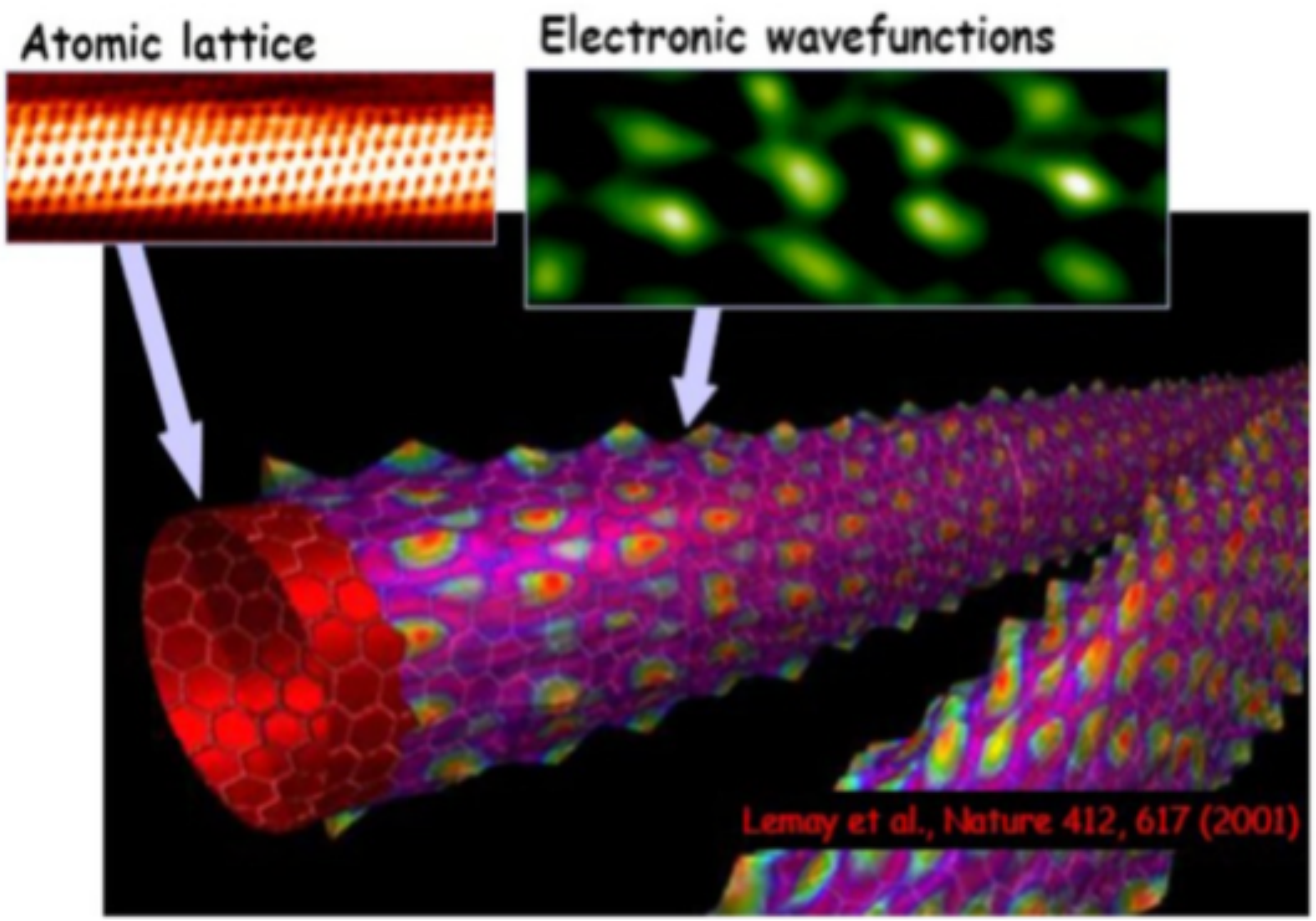




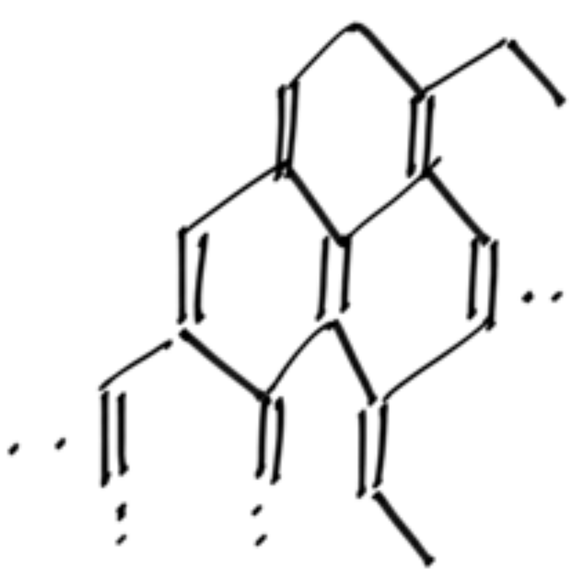
If T is increased, more countings with heavier WIMPs.

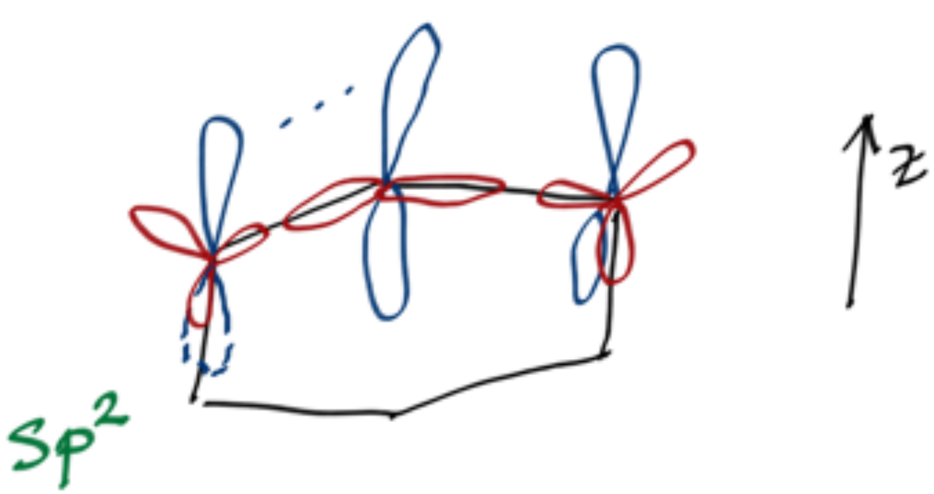
$$T_N^{max} \underset{x \to 1}{\simeq} T_\chi$$

CNT Target

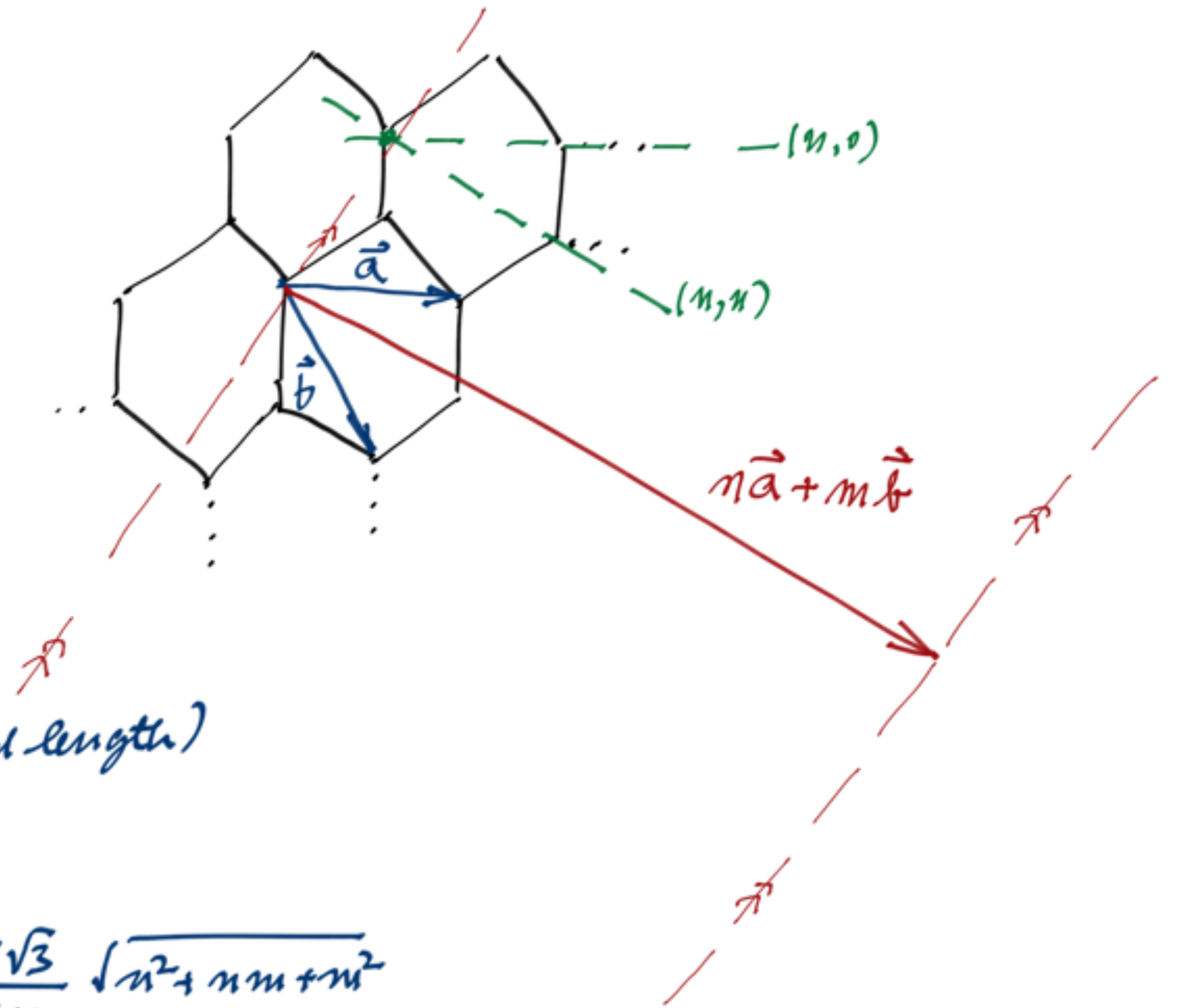


EMPTY CHANNELS





CNT Target



$\ell \simeq 0.14$ nm (bond length)

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

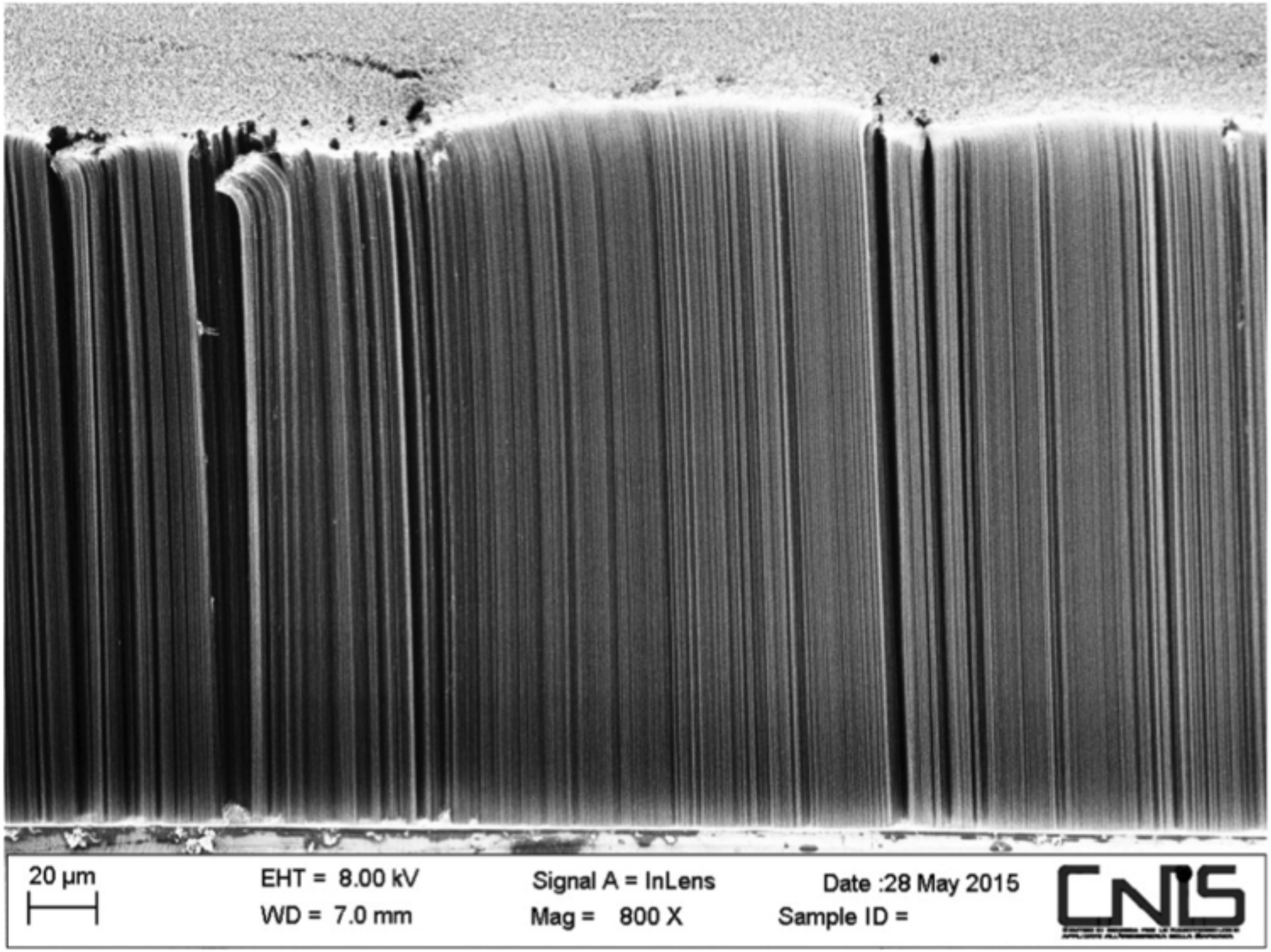
$$R_{CNT} = \frac{\ell\sqrt{3}}{2\pi}\sqrt{n^2+nm+m^2}$$

(n,n) "HARMCHAIR" - METALLIC

(n,m) with $(n-m)$ multiple of 3 - SEMICONDUCT.

$(n,0)$ "ZIG-ZAG"

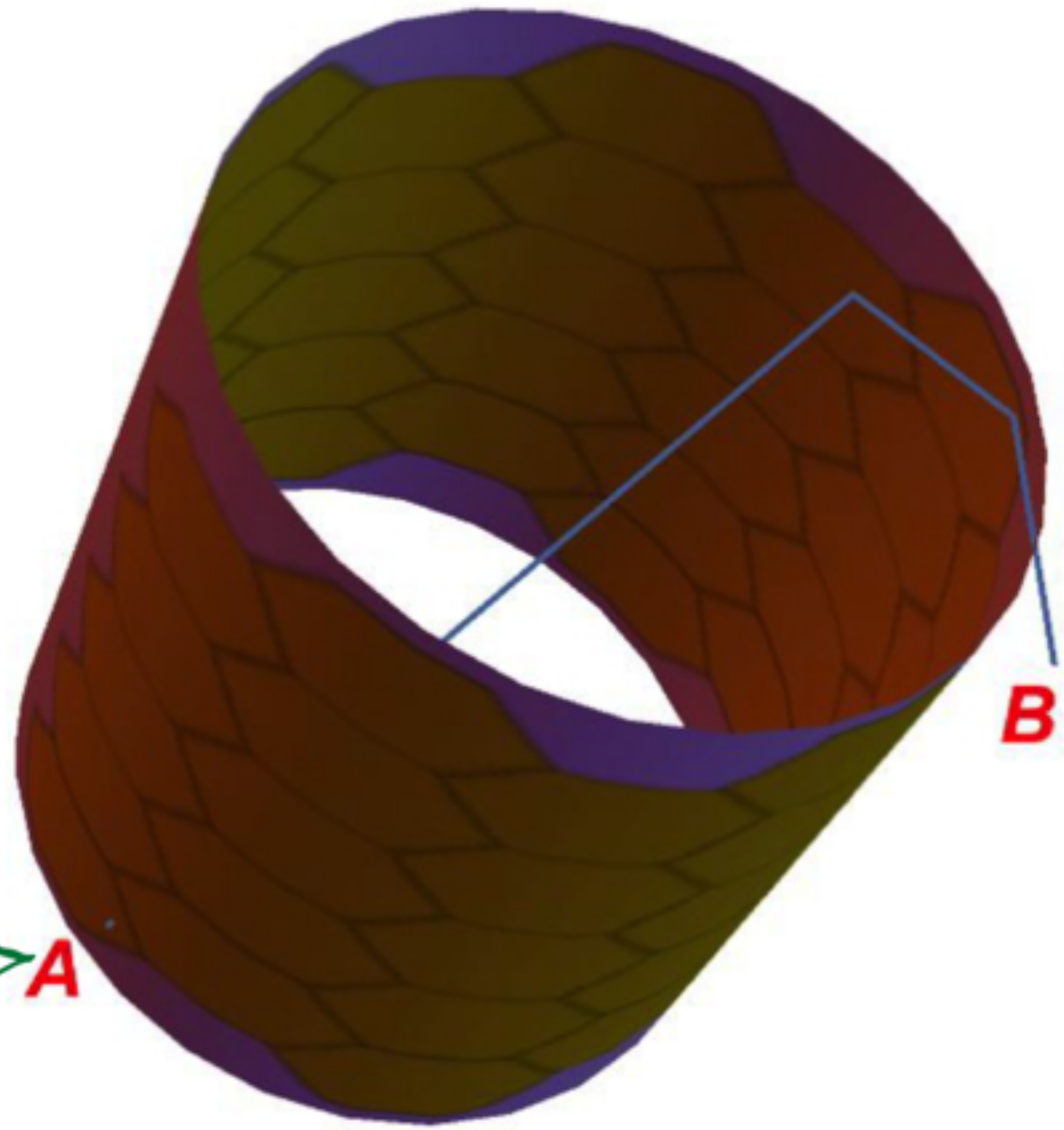
CNTs


20 µm
EHT = 8.00 kV
WD = 7.0 mm
Signal A = InLens
Mag = 800 X
Date :28 May 2015
Sample ID =
CNIS

CNT Target

A: $\sigma_I \sim \frac{|\mathrm{Im}\,\alpha|}{k}$

(1/v law)



B: $\sigma_I \sim \frac{1}{k^2}\, e^{-2\pi/k}$

$\exp\left(-2\pi Z_1 Z_2 \frac{\alpha}{v}\right)$

(T,θ) with $M_\chi = 11\,\mathrm{GeV}$.

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 $C \to C^{4+}$ costs $\sim 147\ eV$

C^{5+} 〃 $\sim 539\ eV$

C^{6+} 〃 $\sim 1029\ eV$

M_χ (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

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

$$= \sum_{\text{chains}} \bar{U}\left(\vdots\right)$$ — each $\bar{U}$ as a Fourier series of azimuthal harmonics

$$q = gcd(2m+n, 2n+m)$$

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

$$U_\nu(r) = 4\sqrt{\pi}\,\sigma Z^2 e^2 \left(\frac{R}{r}\right)^{1/2} \sum_{j=1}^{4} a_j b_j\, e^{-b_j^2(r^2+R^2)} \times$$

$$\times\, e^{2b_j^2 rR\left[\sqrt{1+\xi^2} - \xi \ln\left(\xi+\sqrt{1+\xi^2}\right)\right]}$$

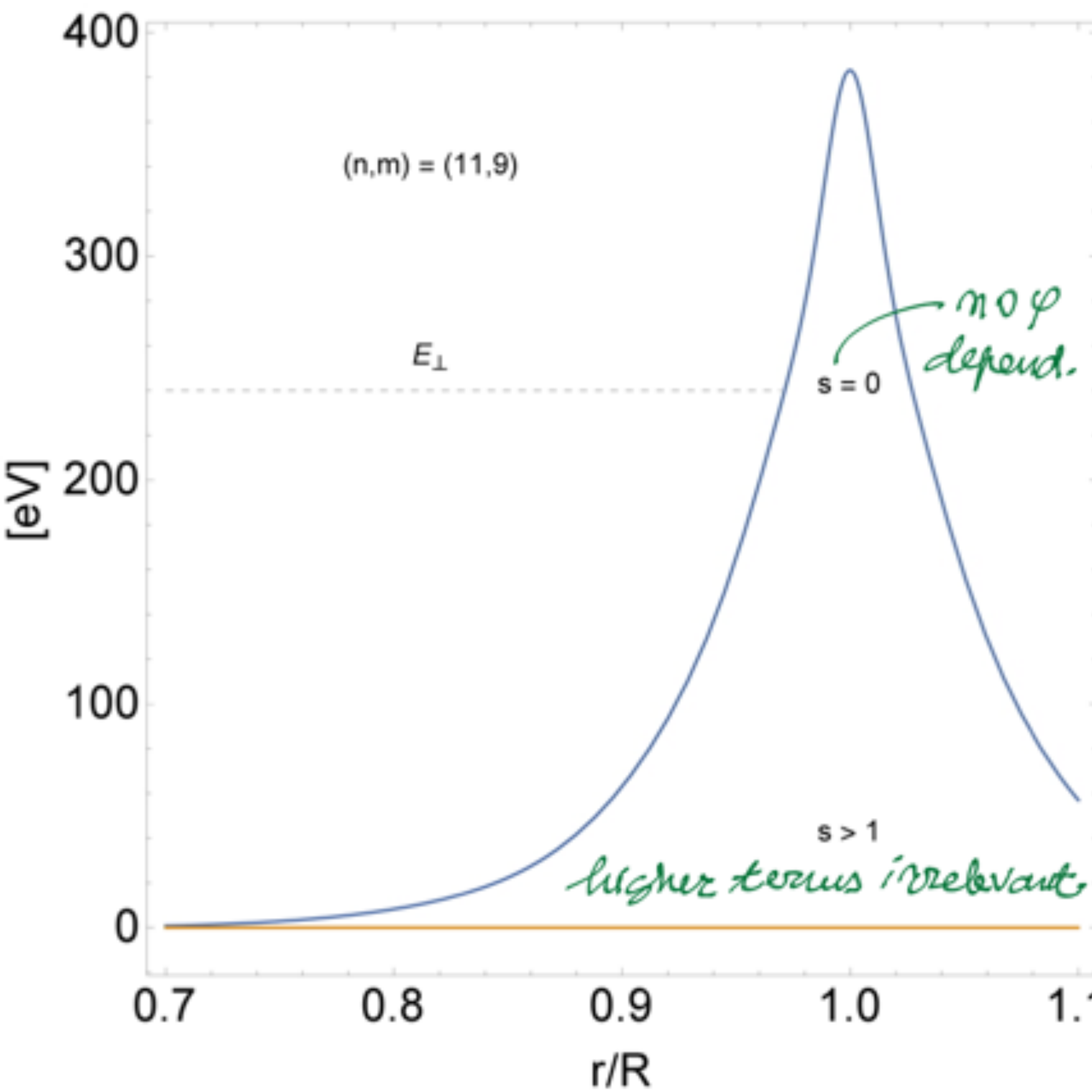
$$\xi = \nu / 2b_j^2 rR$$

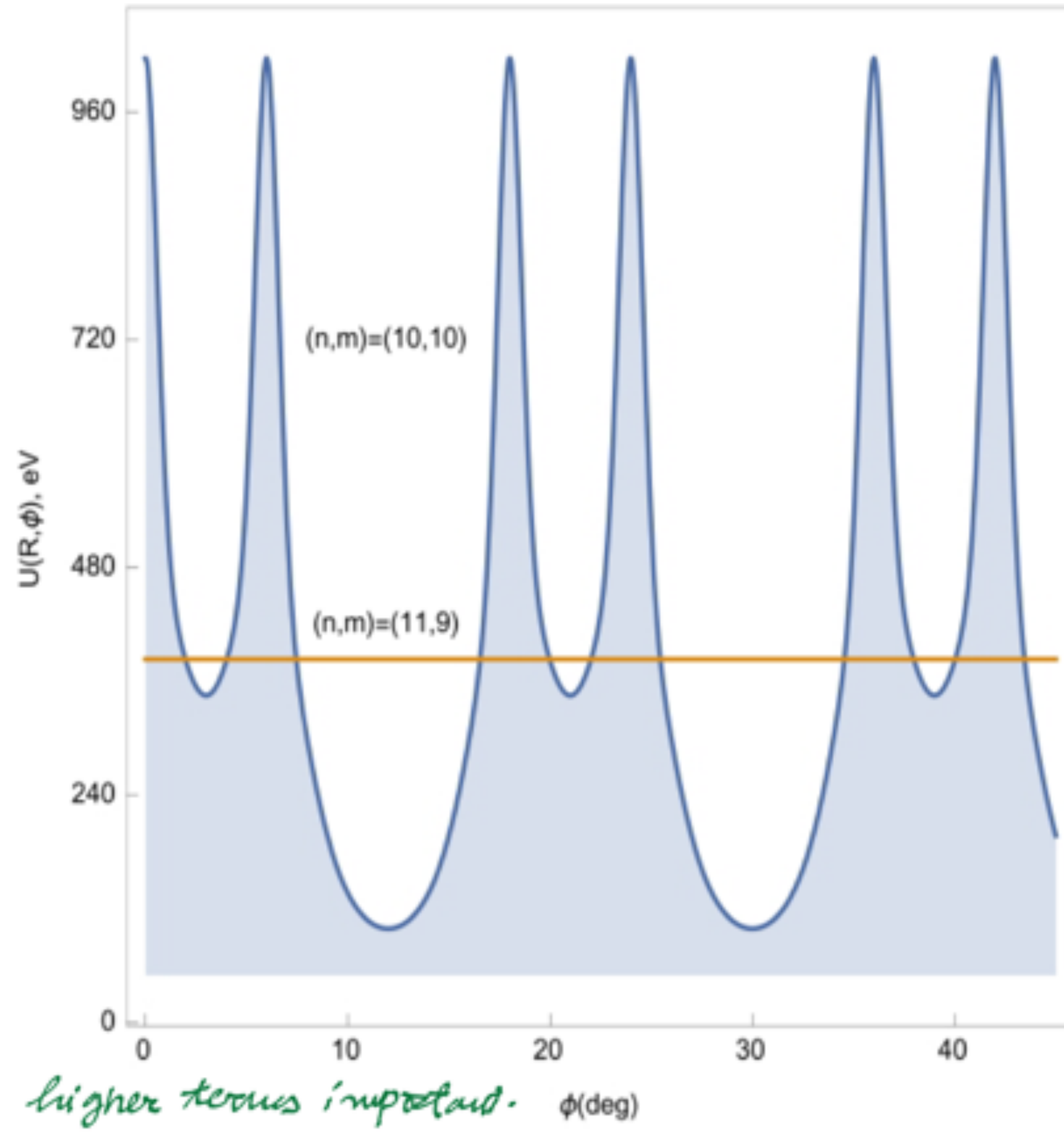
$$\sigma = 4/\ell^2 3$$

a_j [nm²], b_j [nm⁻¹] reported in

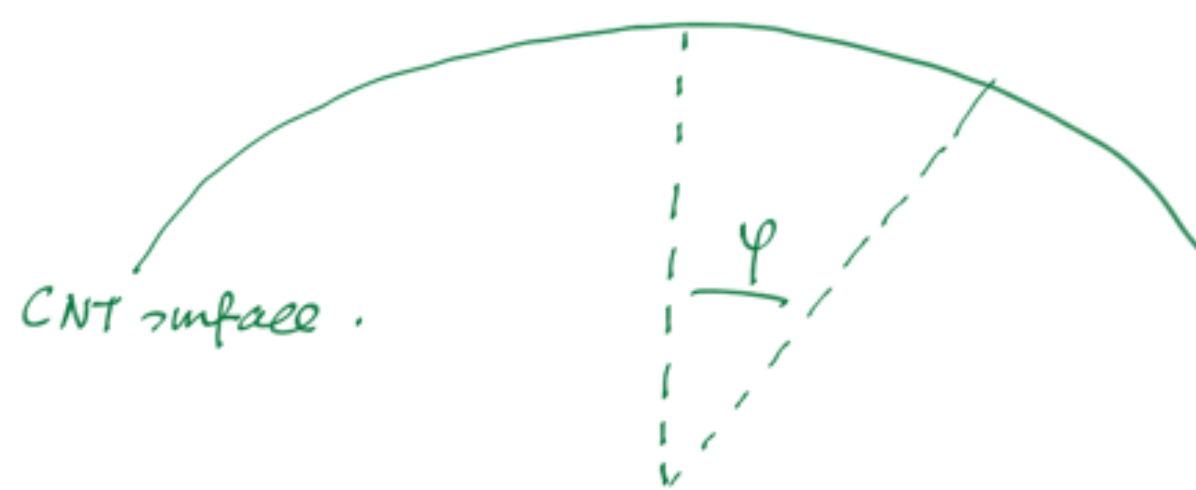
ARTRU et al. Phys. Rept. 412, 89 (2005)

CNT POTENTIALS

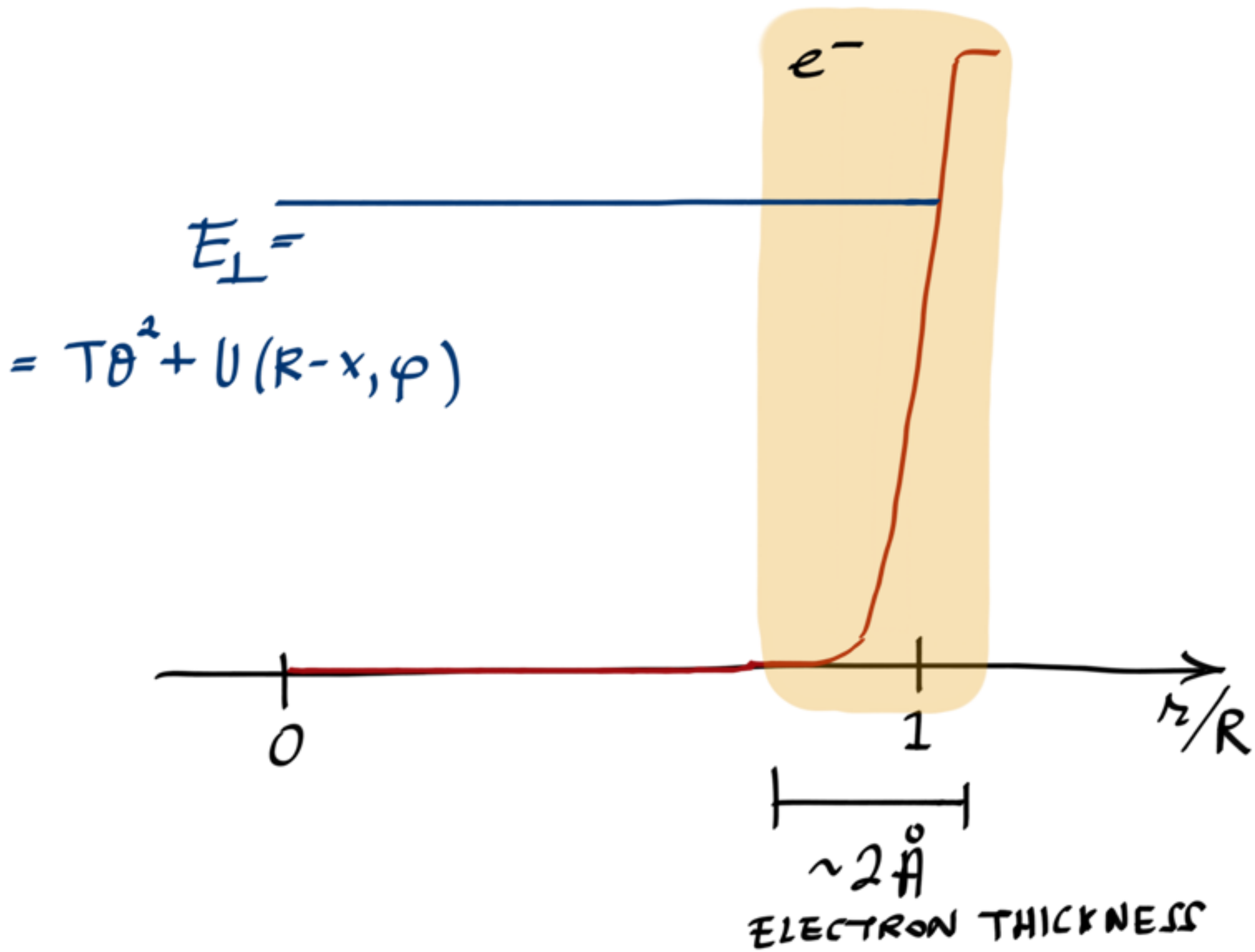




(For a C^{6+})

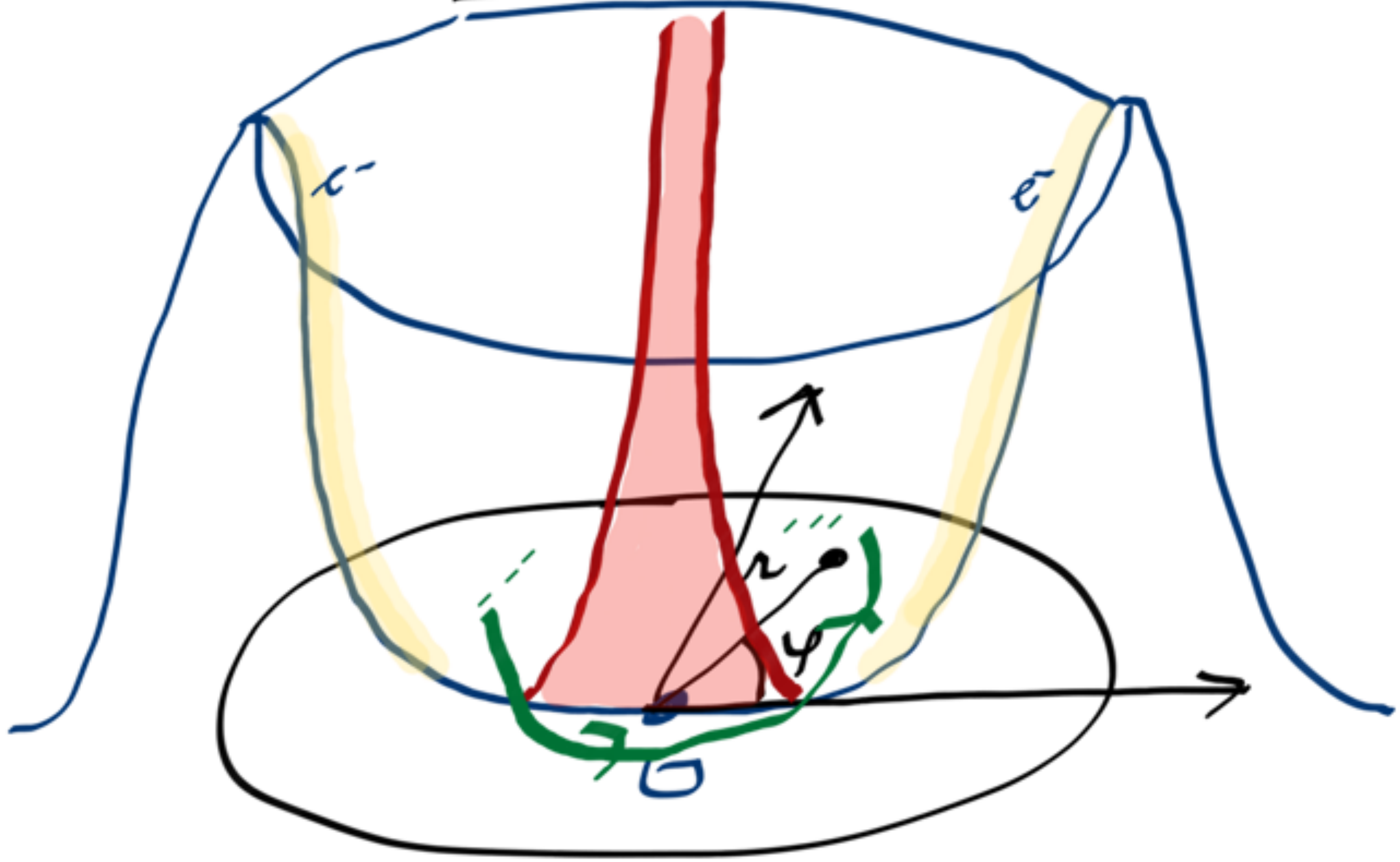


CHANNELS



e^-
$E_\perp =$
$= T\theta^2 + U(R-x, \varphi)$
0
1
r/R
$\sim 2\,\text{Å}$
ELECTRON THICKNESS

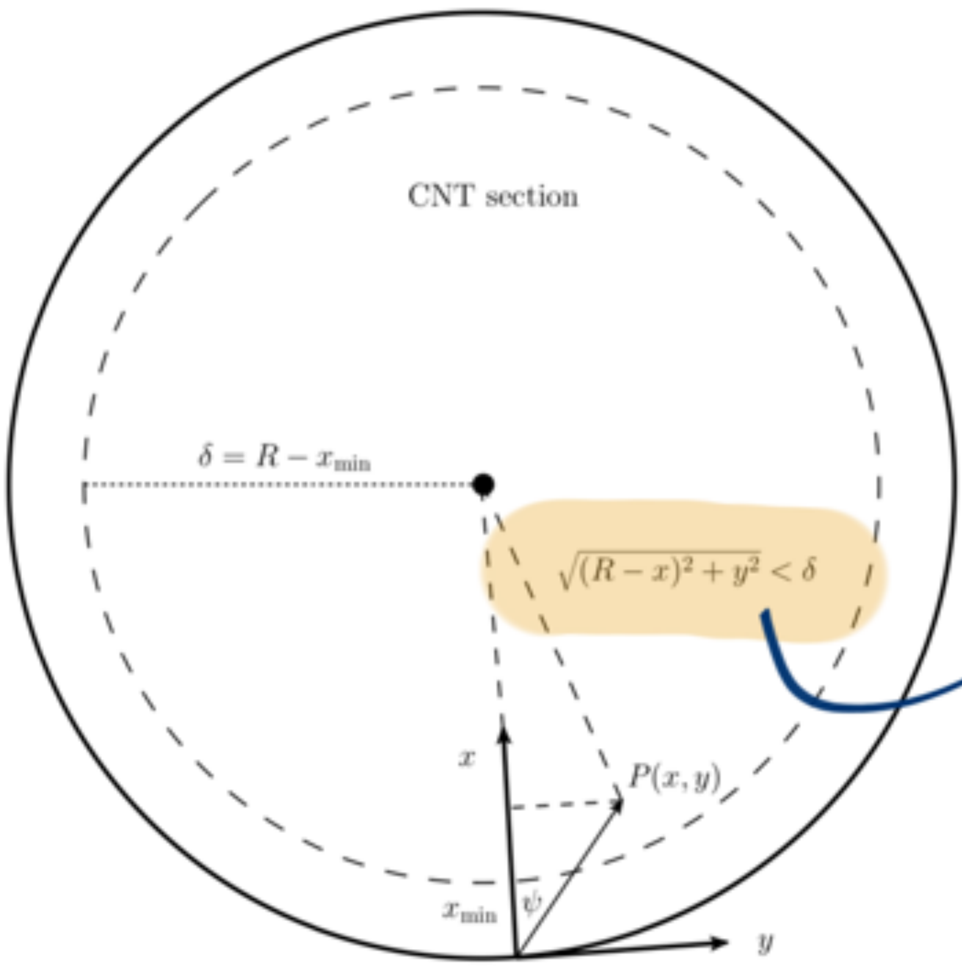
Paths



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

Smaller values of L push closer to the boundaries (where e^- are)
→ more frequent "dechannelings" or "dead events"

Channeling conditions



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

$\Rightarrow x_{min}$

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

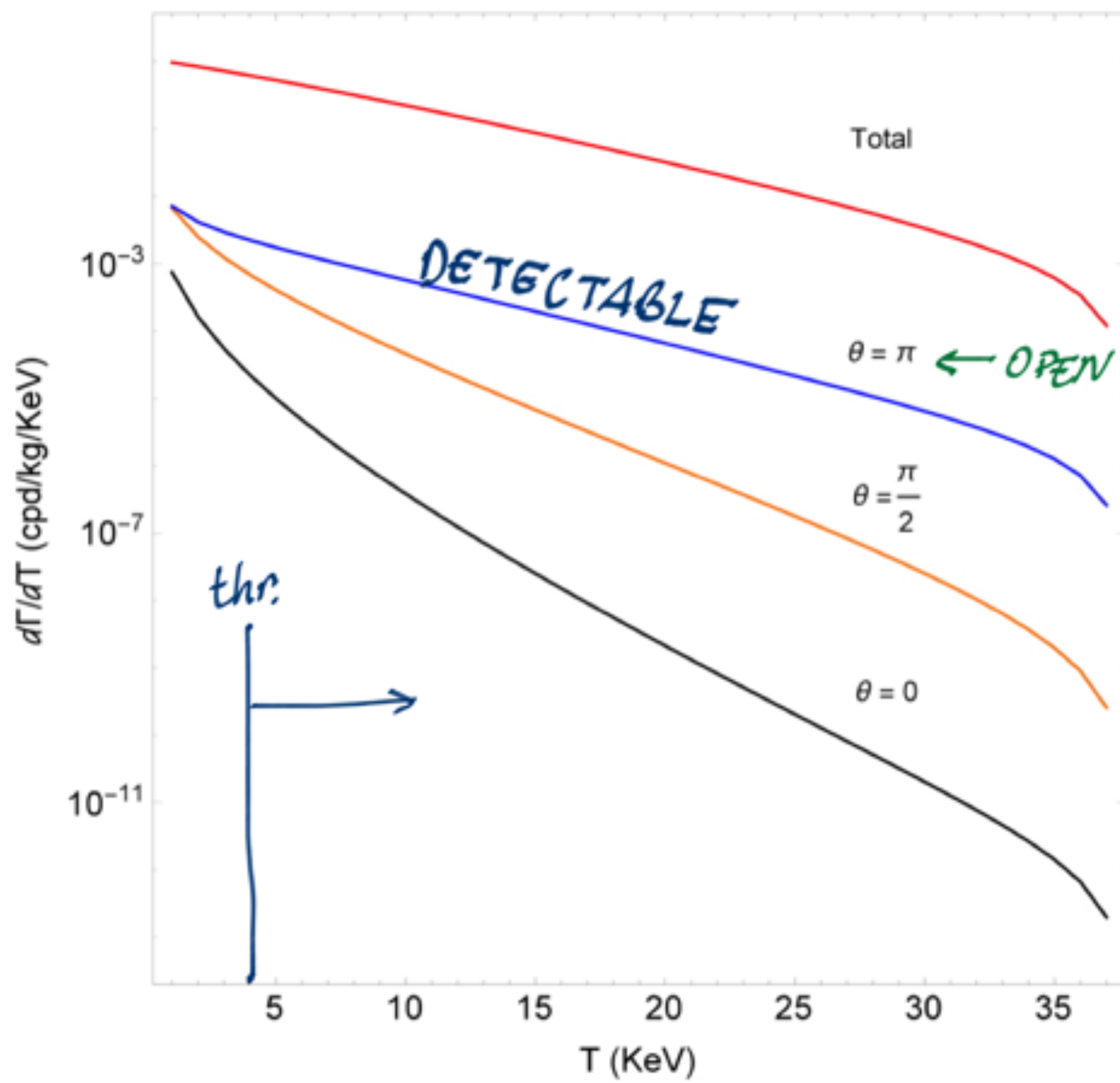
$\rightarrow$ defines $\mathcal{R}$

$$\left.\begin{aligned} u_\perp &= 0.0075\,\text{nm} \\ u_\parallel &= 0.0035\,\text{nm} \end{aligned}\right\} @\ \text{room}\ T^*$$

From Debye theory.

G.B. Gelmini
1201.4560

Channelings

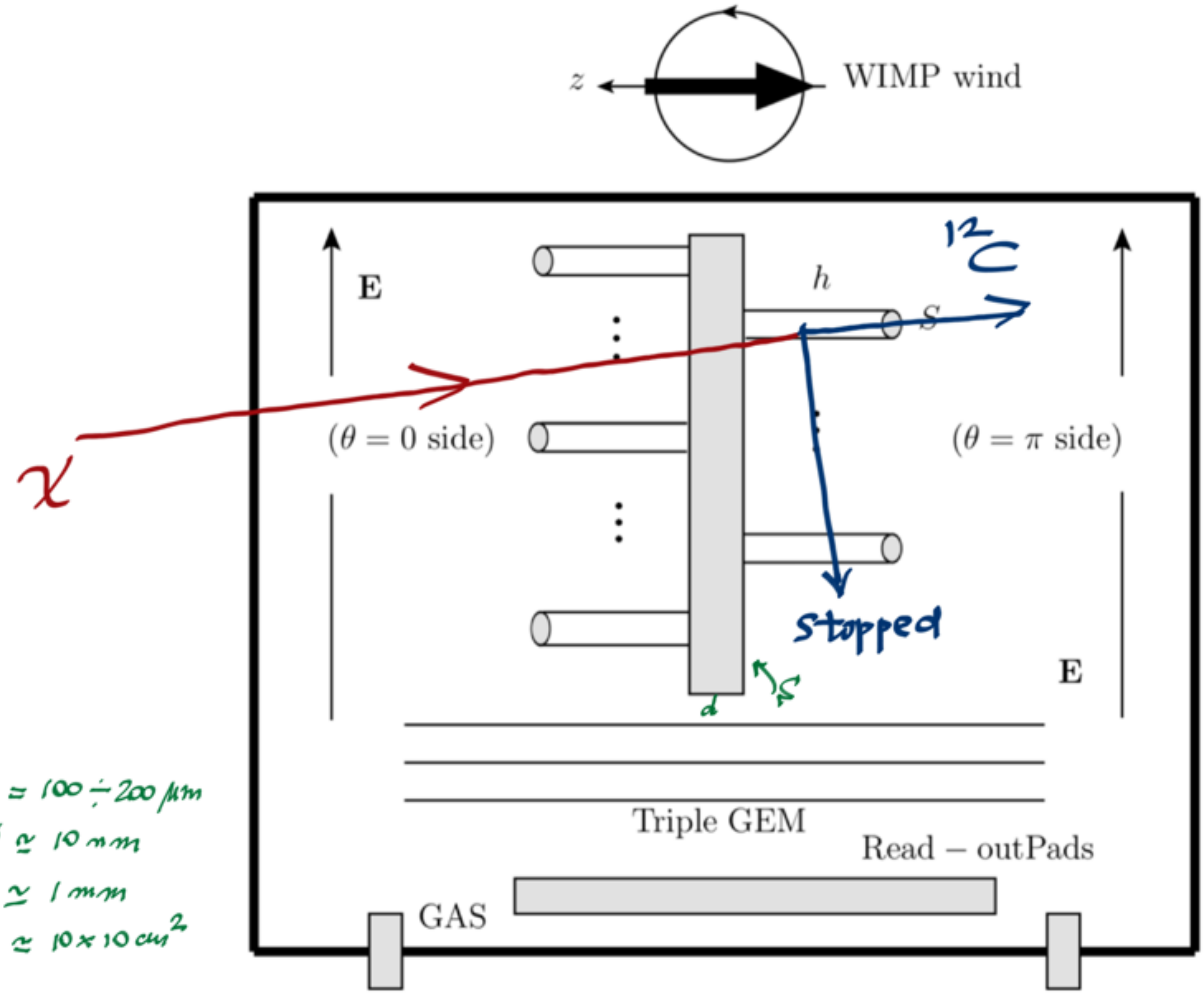


CAPPARELLI, CAVOTO
MAZZILLI, POLOSA
PHYS. DARK. UNIV.
9-10 (2015) 24
11 (2016) 79

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

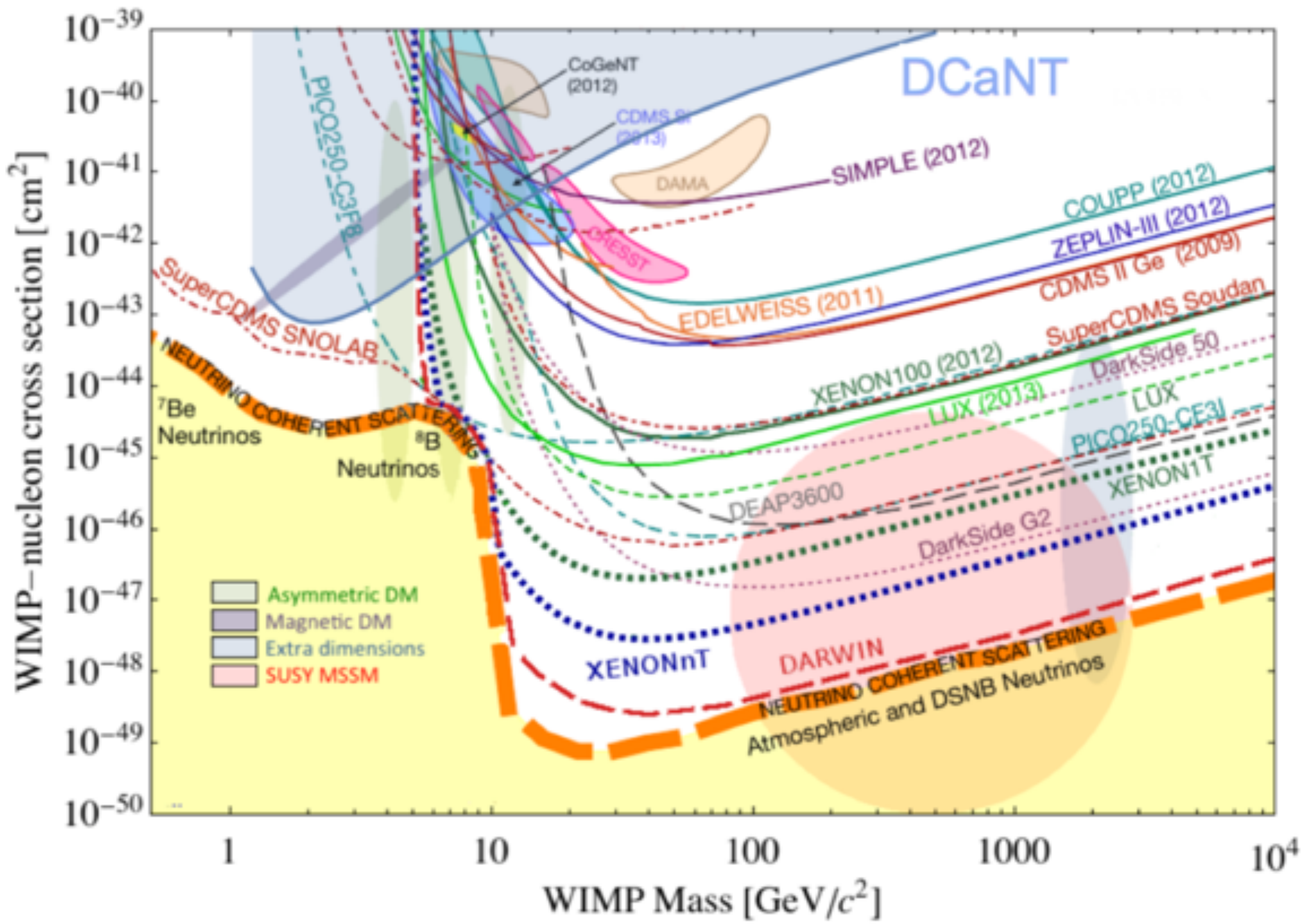
HISTOGRAM OF THE CHANNELED EVENTS UNDER THE VERY RESTRICTIVE CONDITIONS MENTIONED BEFORE. RECHANNELINGS OR INTER-CNT TRAPPING NOT INCLUDED HERE

DIRECTIONAL DETECTOR



$h = 100 \div 200\ \mu m$
$\phi \simeq 10\ mm$
$d \simeq 1\ mm$
$S \simeq 10 \times 10\ cm^2$

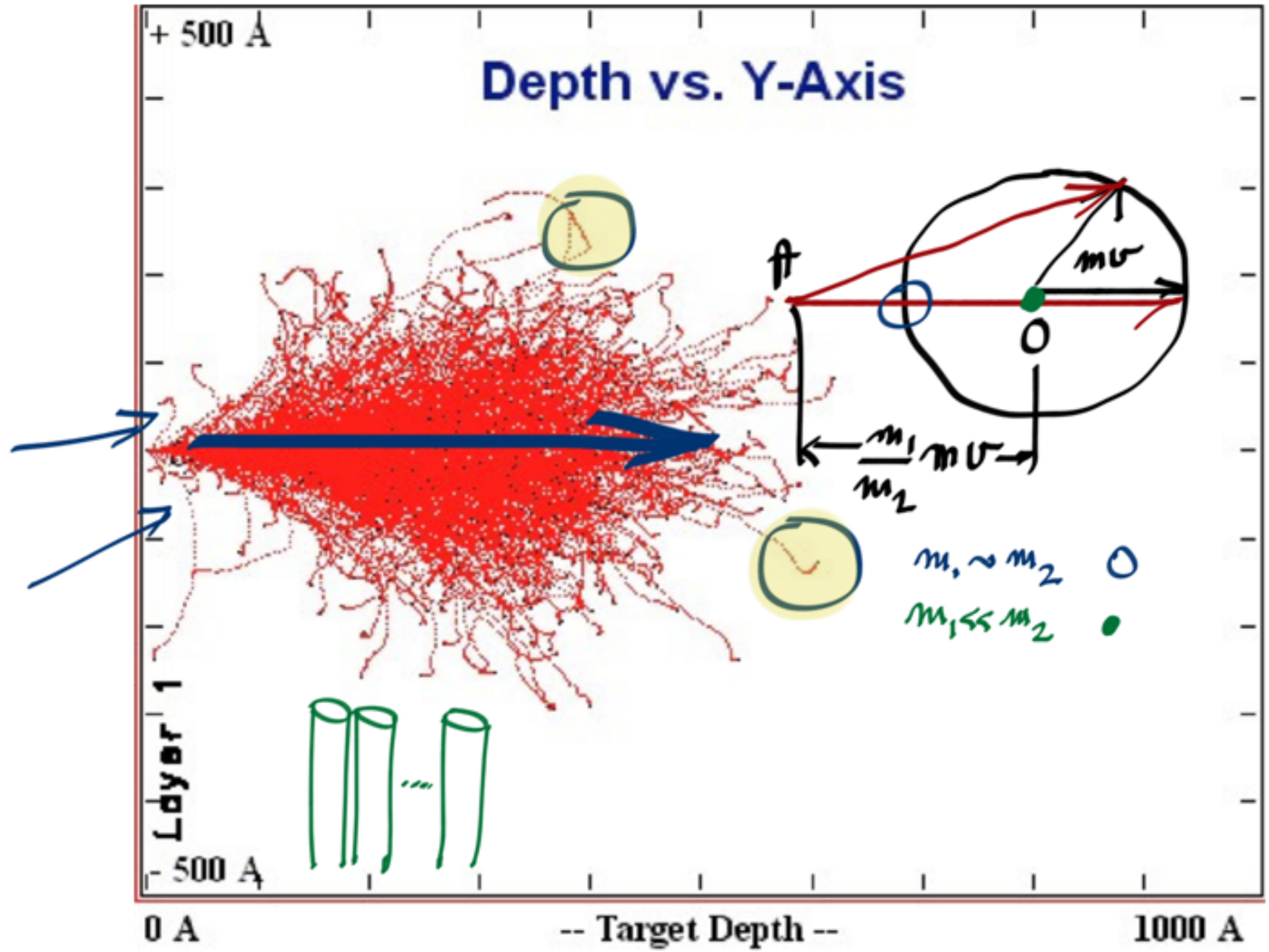
Sensitivity



- 100 layers, 1 m² each
- Compact readout → few m³ volume
- Rotated tracking CYGNUS
- Sensitivity for 0.4 Kg y

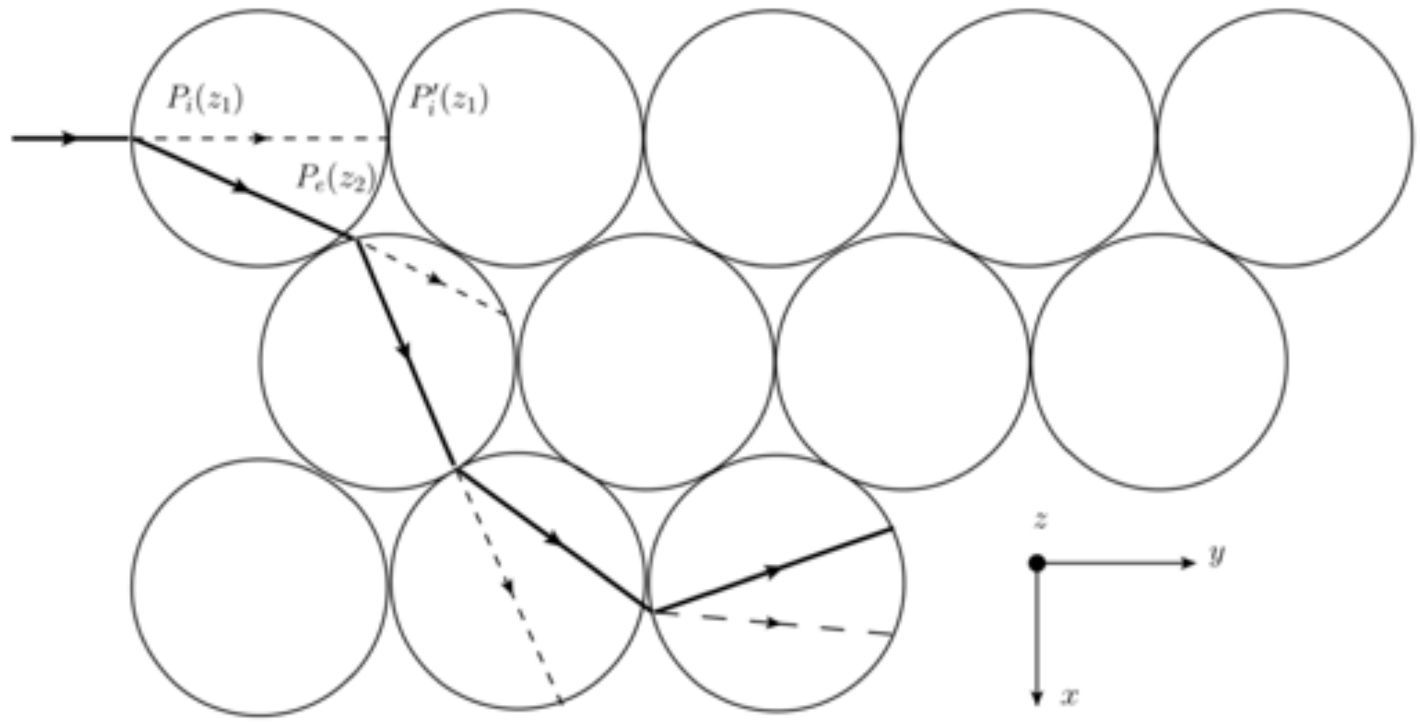
(CCNT trapping C ions detected down to 1 KeV)

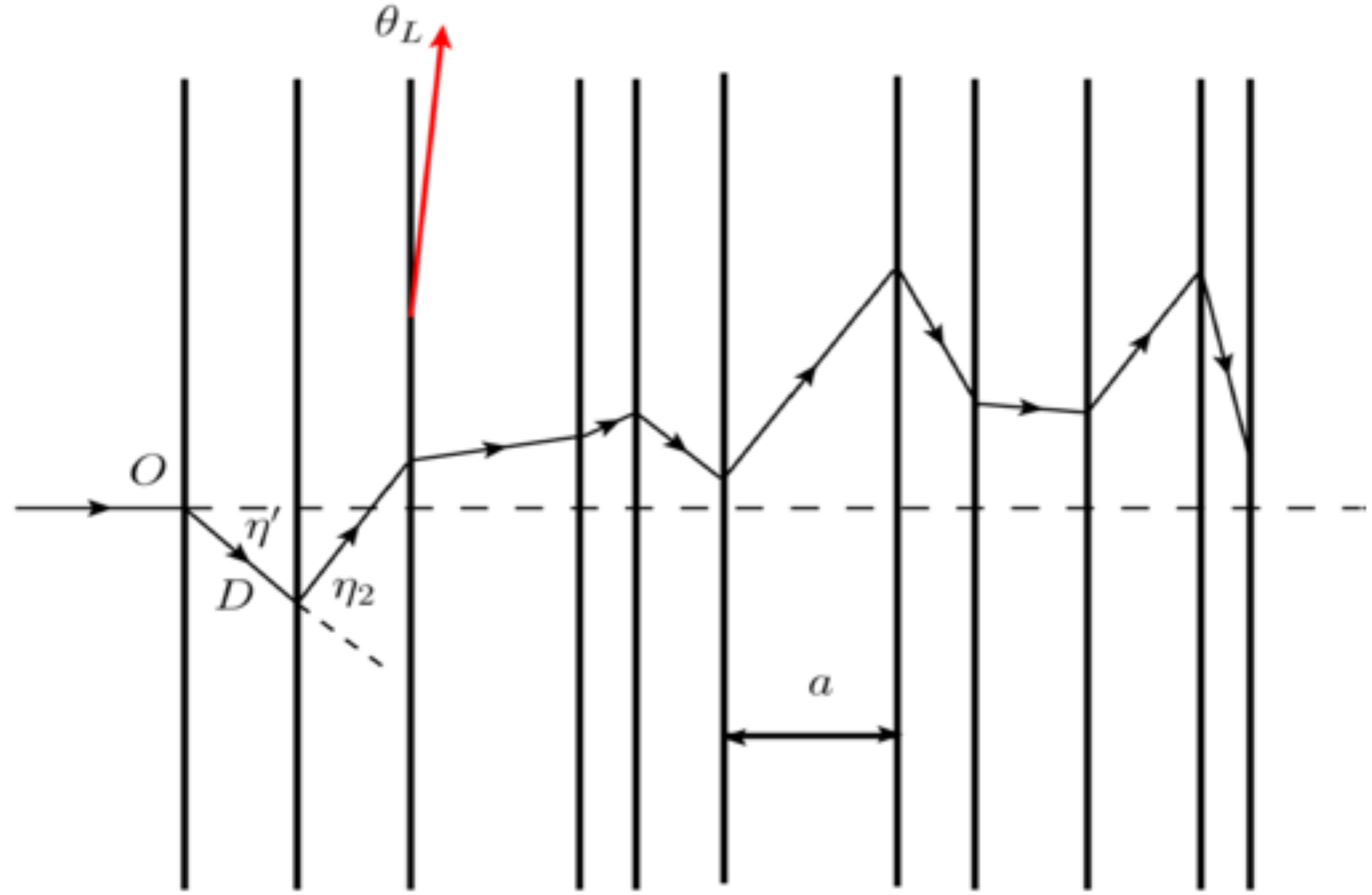
RE-CHANNELINGS



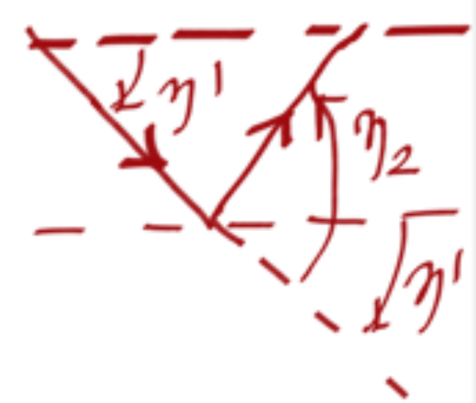
θ_s from distr. $\cos\theta_s / \sin^3\theta_s$ $(m_1 \sim m_2)$

RE-CHANNELINGS

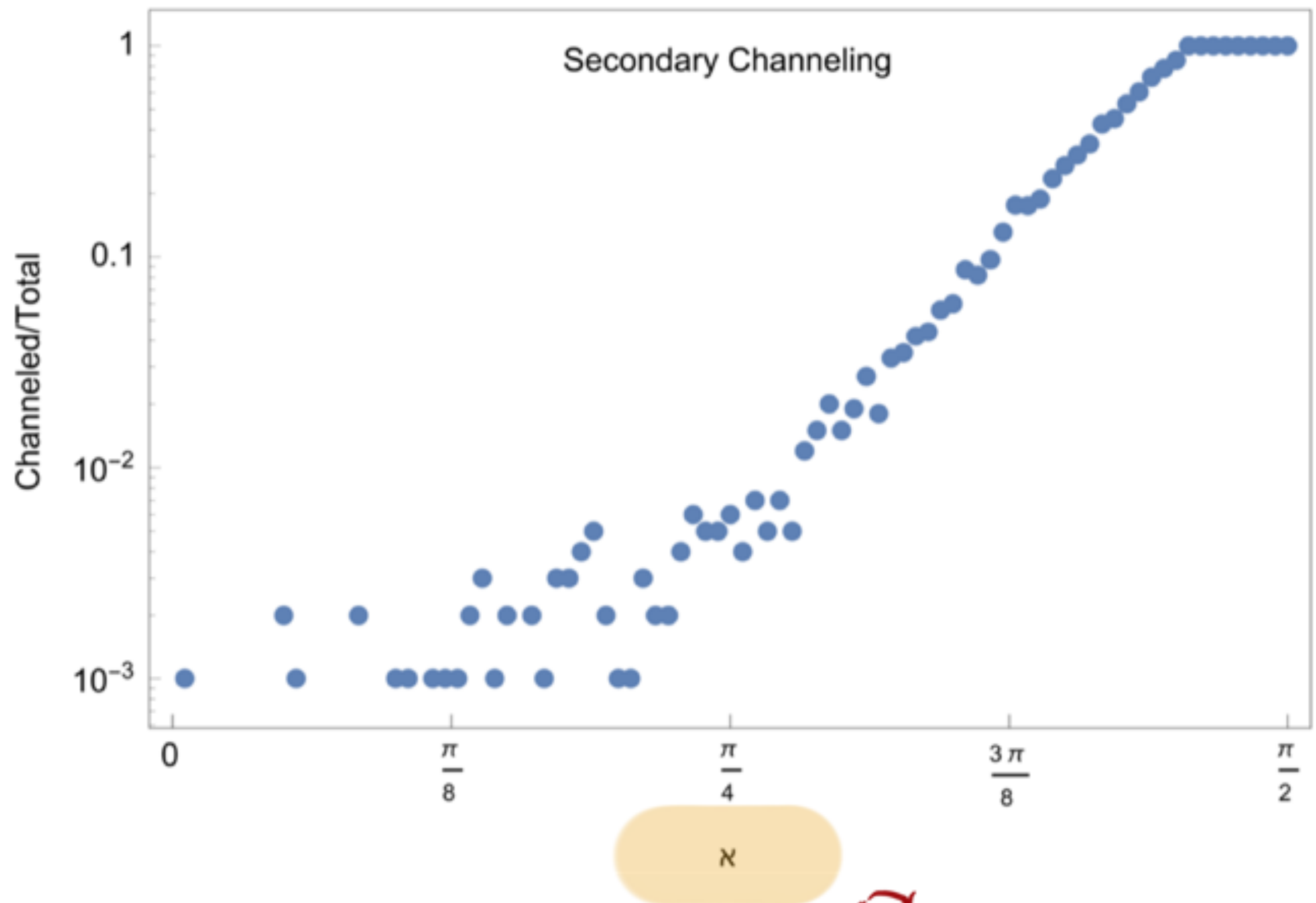


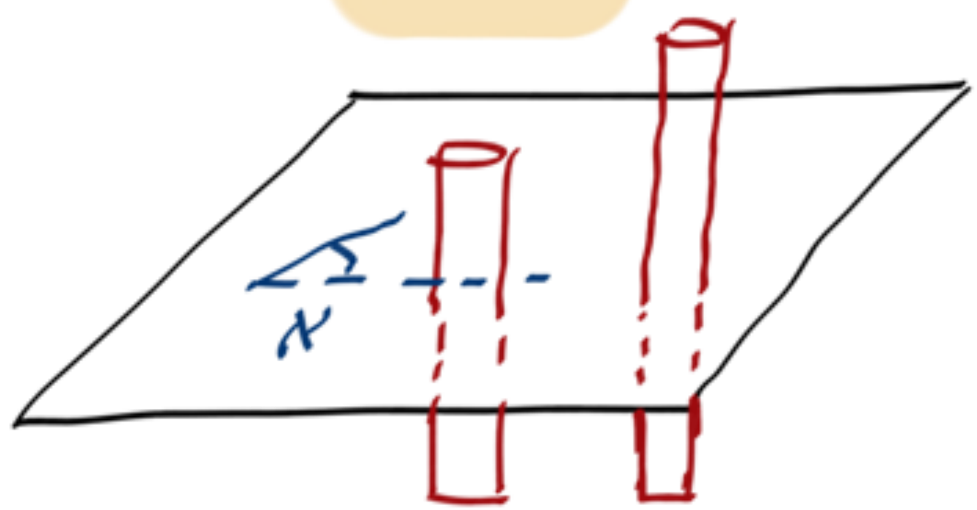


PROJECTED
SCATT. ANGS.

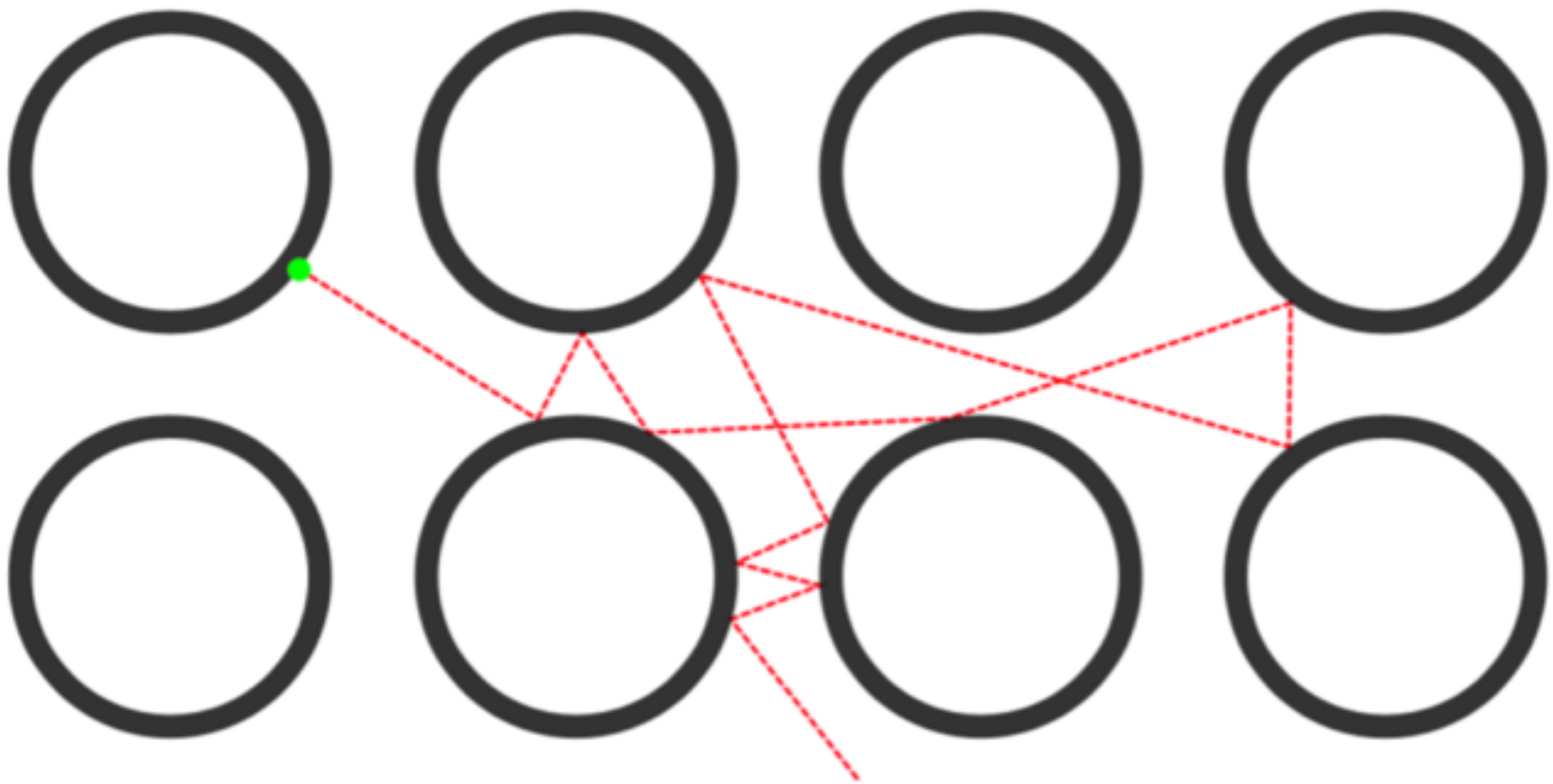


RE-CHANNELINGS





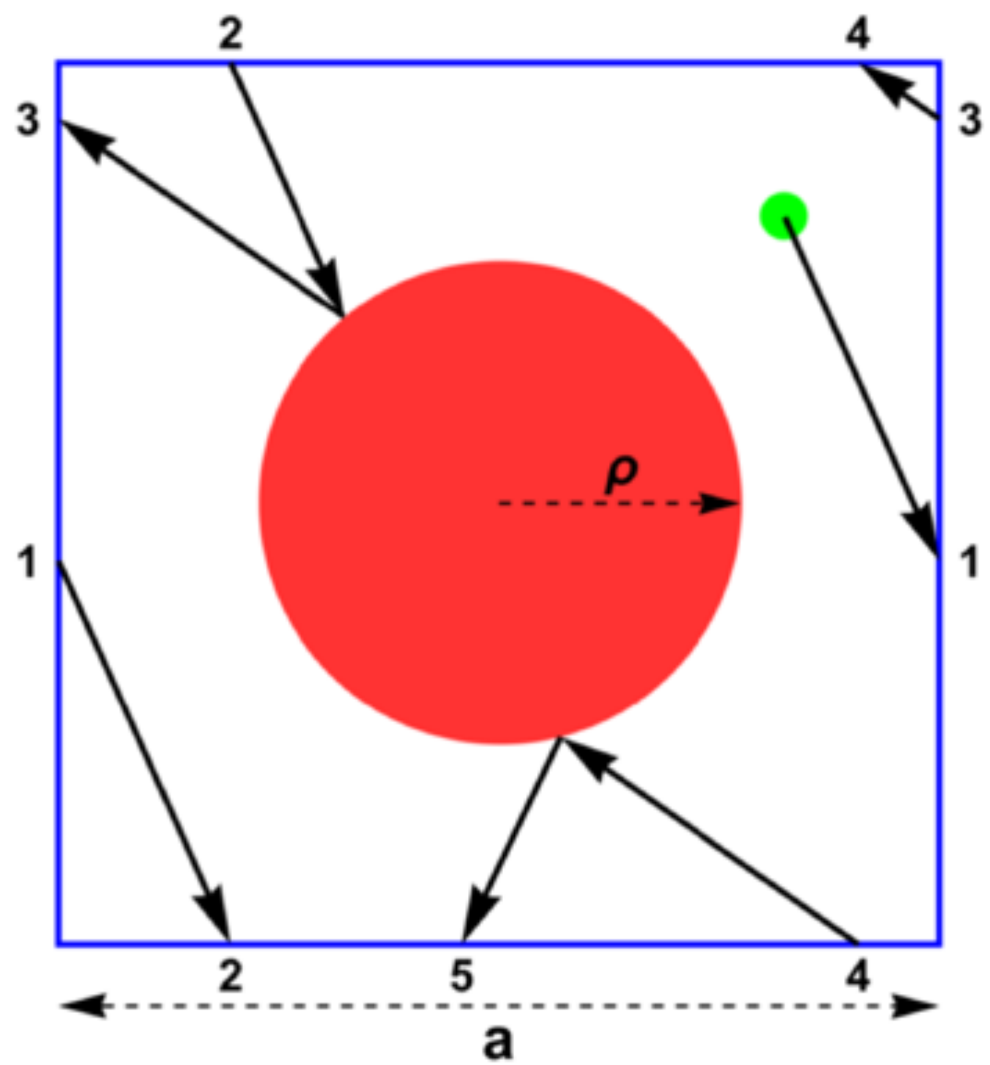
Billiards



Billiards

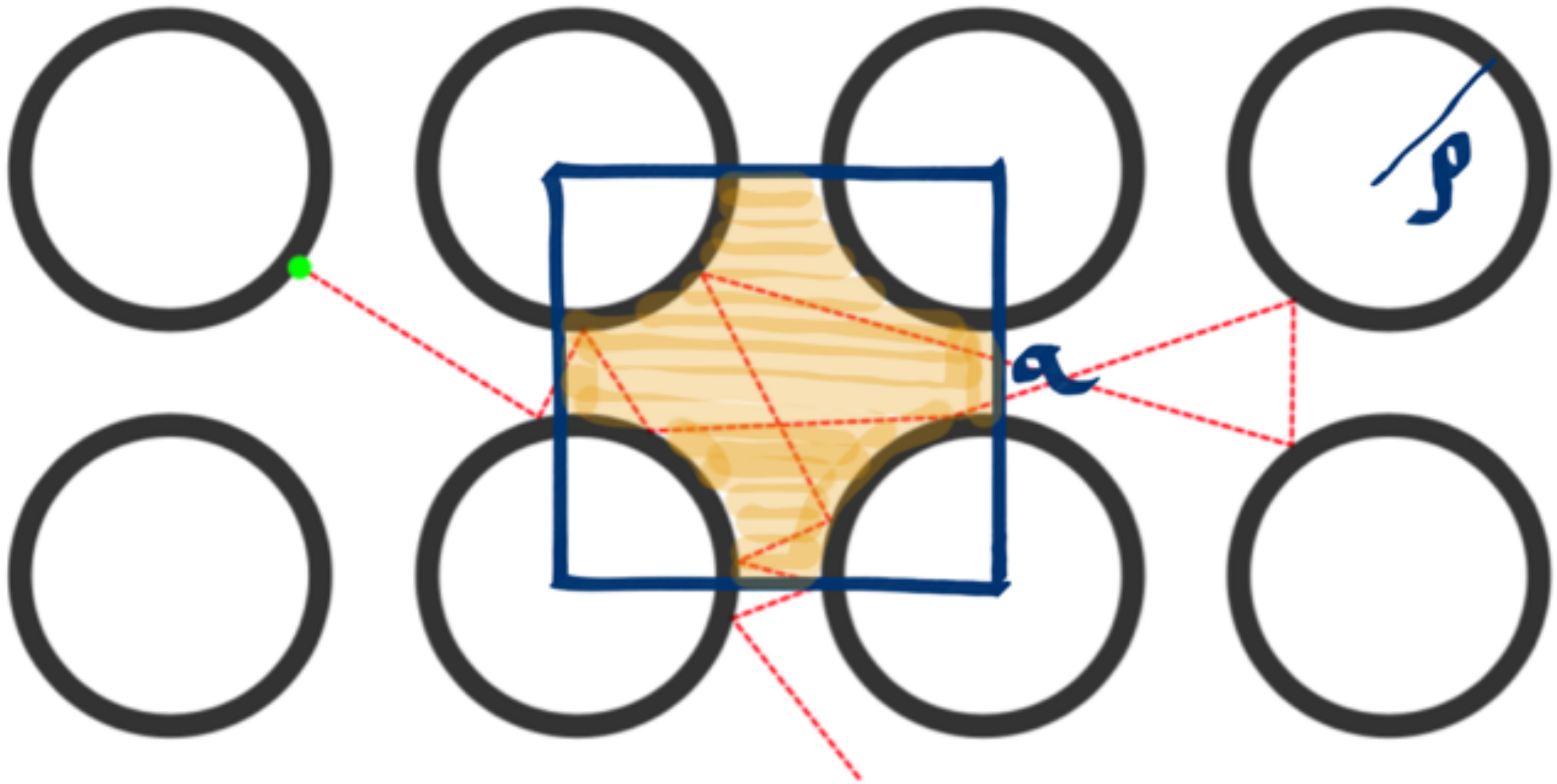
Problem: a particle enters the CNT forest with $(v_{\parallel}, v_{\perp})$.

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



Billiards

$$\boxed{\tau = n_{hops}\,\tau_R}$$

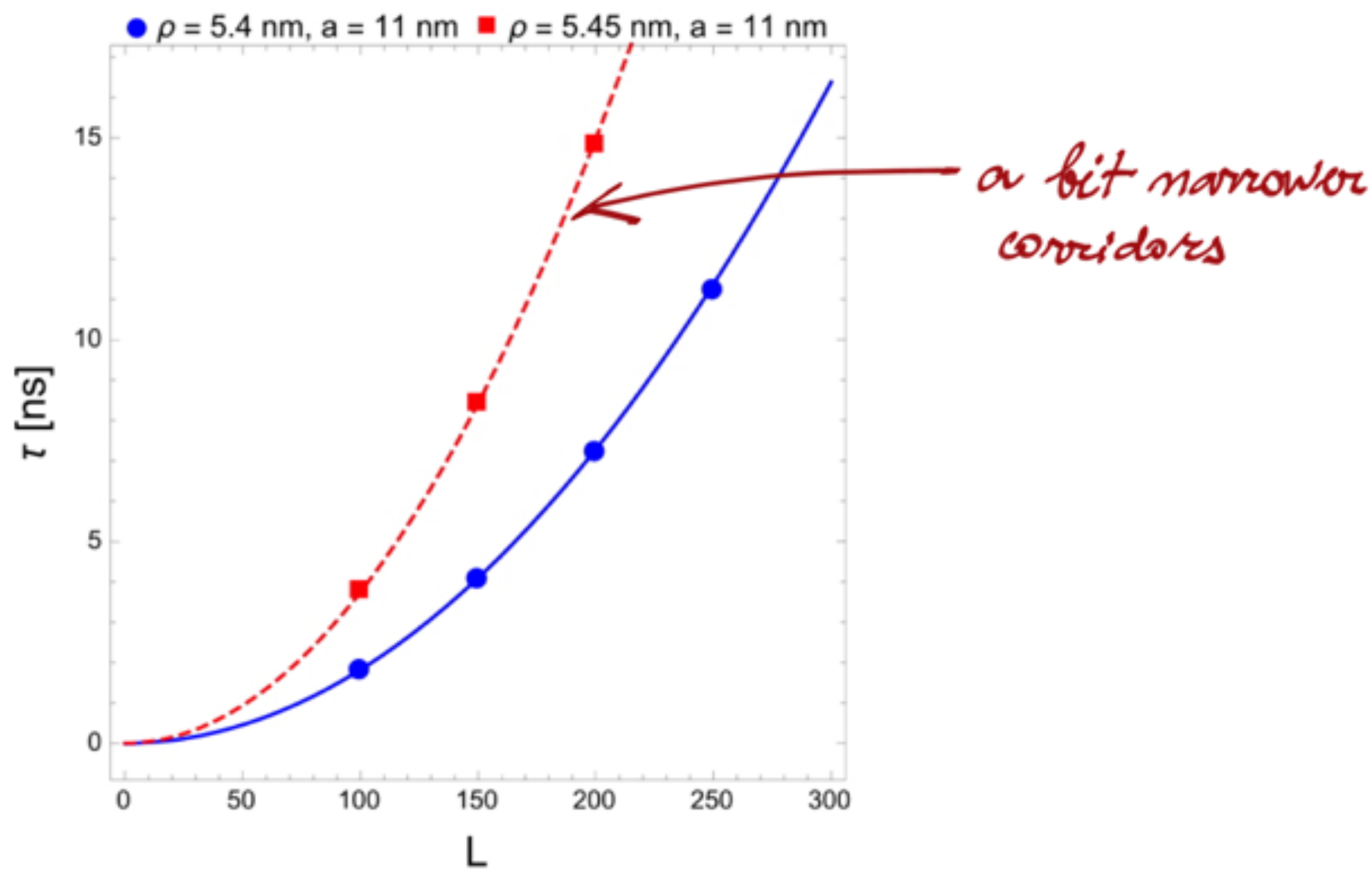


$\delta = a - 2\rho$

$\delta \ll a$ = NARROW CORRIDOR REGIME

$$\tau_R = \frac{\pi\left(a^2 - \pi\rho^2\right)}{4\, v_\perp\, \delta}$$

Billiards

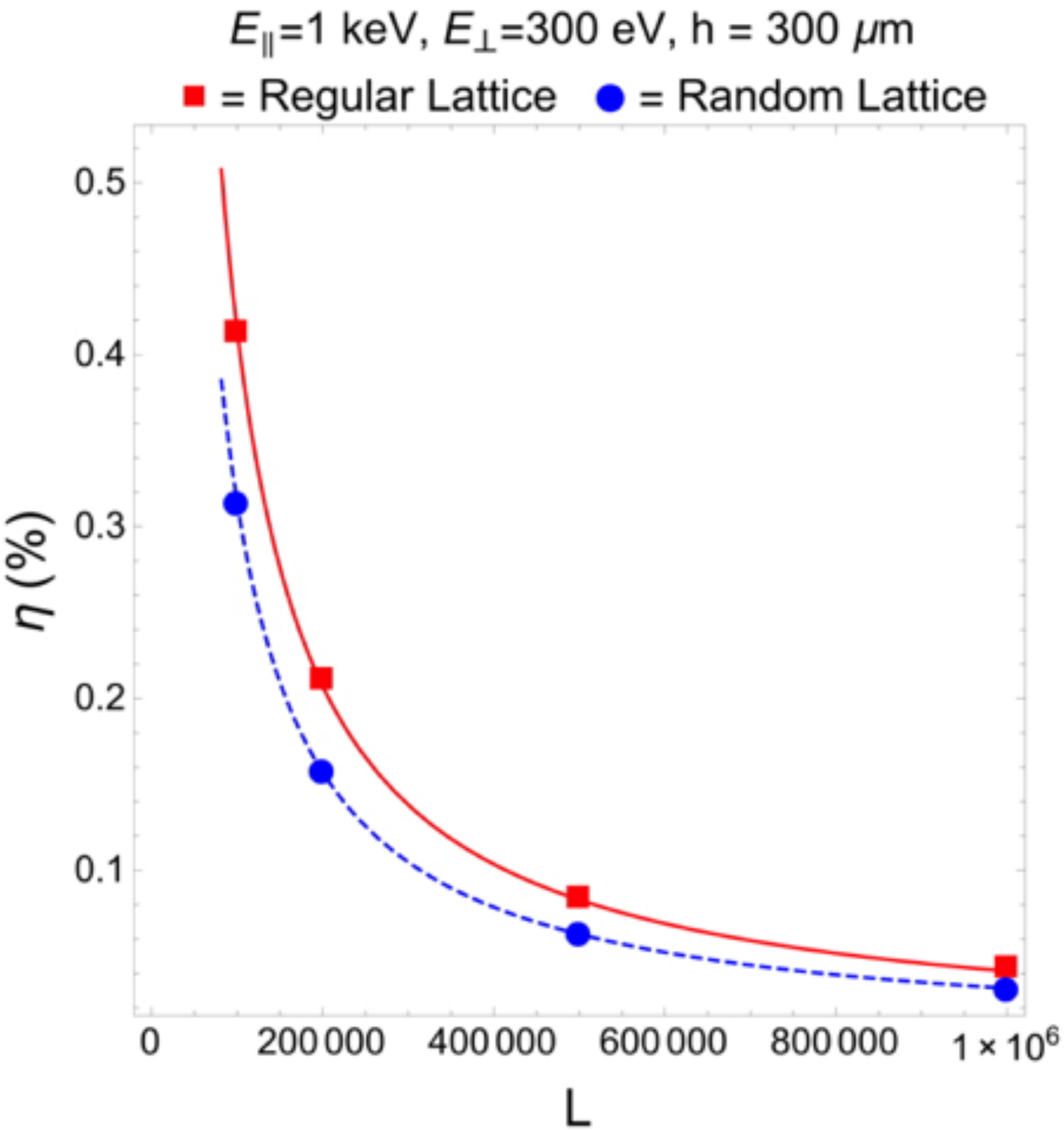


find $n_h \simeq \frac{L^2}{7}$; $E_\perp \simeq 300\,eV$

τ = time needed to exit from the billiard.

MEAN EXIT TIME

Lateral losses



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

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

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 $E_{\parallel} > 1\,\mathrm{keV}$

2) Bottom events: opposite

3) Dead events: ions reach energies below det. threshold while traveling in the array

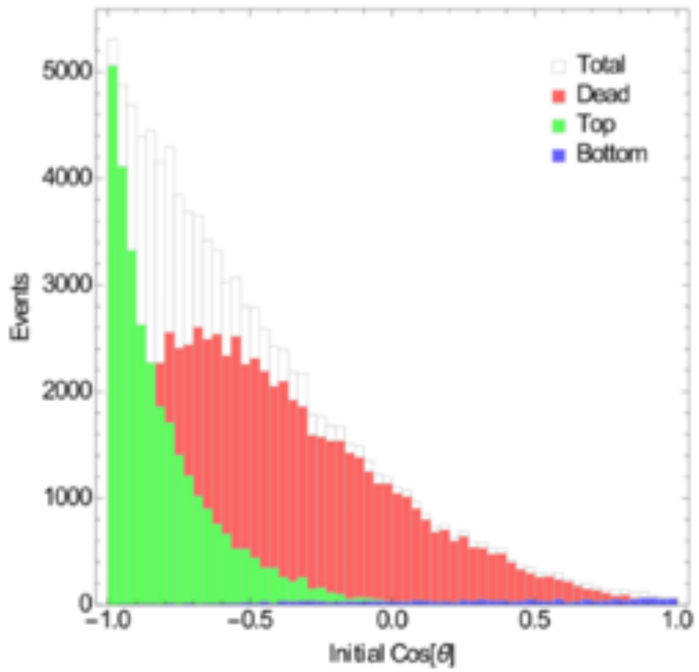
4) Side events: lateral losses

With 10^5 ion trajectories we get

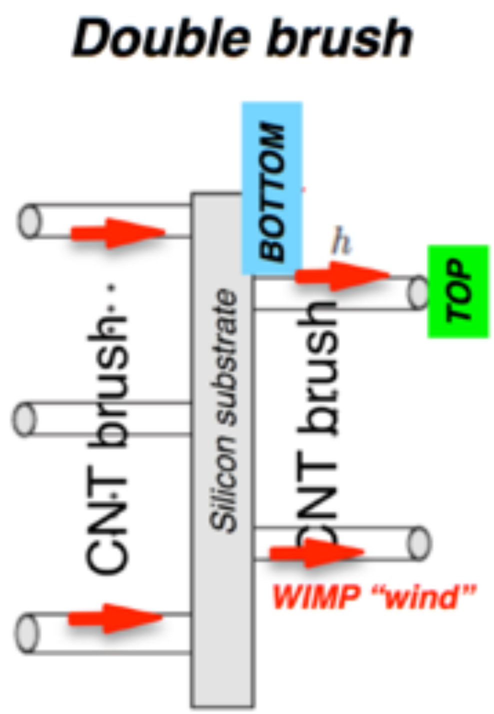
Top	Bottom	Side	Dead	Total
30802	1786	447	66965	100000

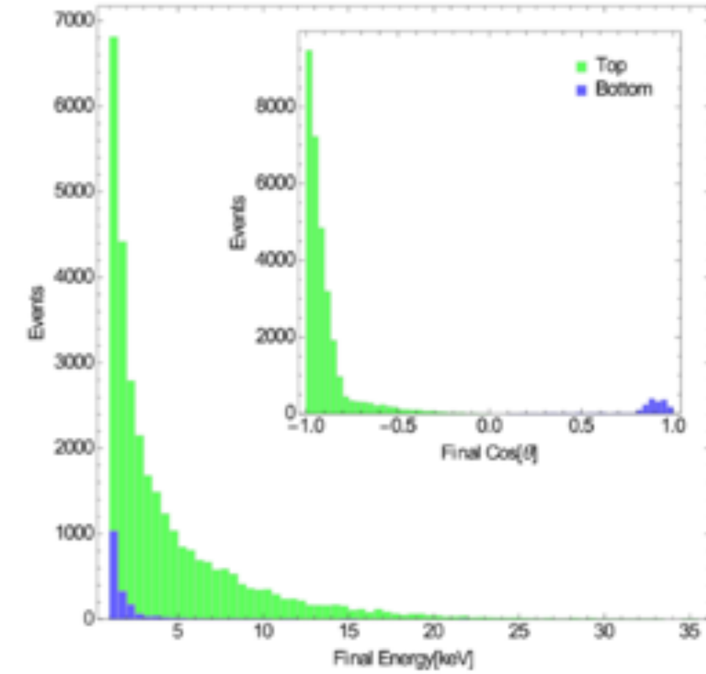
$\sim 1/20$

Energy losses



Initial C ion direction





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 $\simeq 0.4\%$.
- 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.

$\theta_A \sim 4^\circ$ CNT $\to$ $\theta_A \sim 35^\circ$ CNT ARRAY

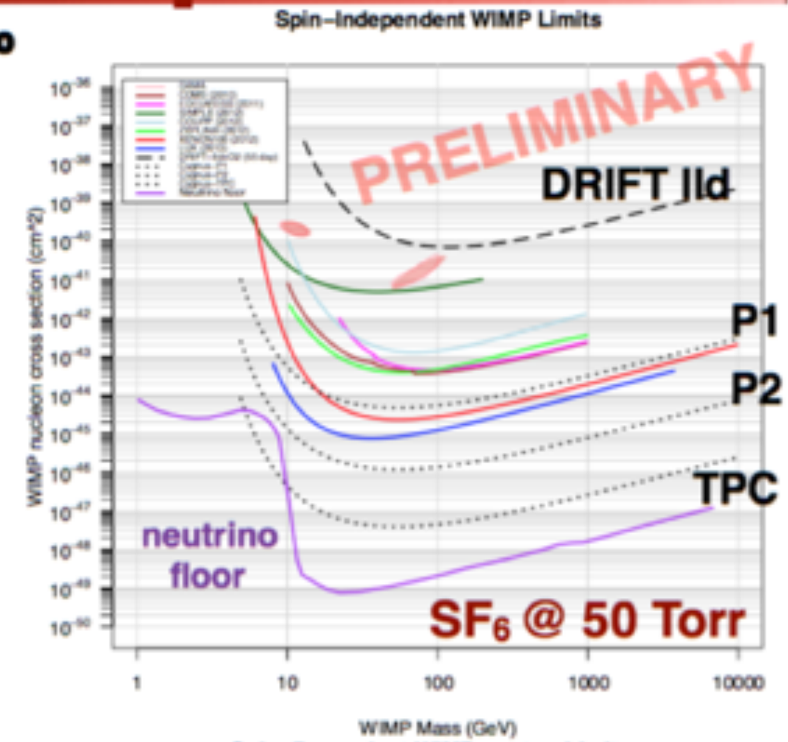
CYGNUS-TPC proposal

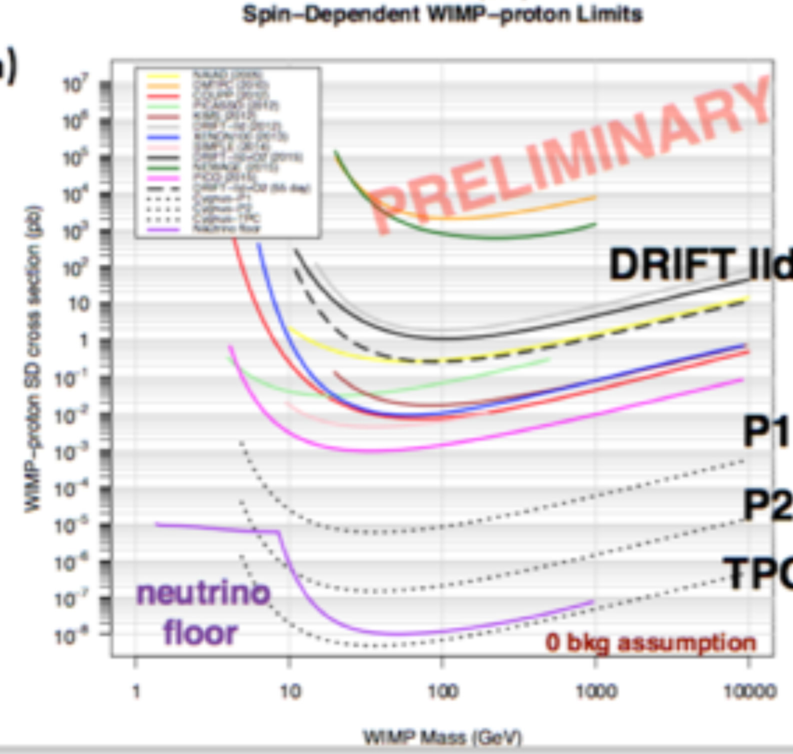
- Galactic Nuclear Recoil Observatory: **measure WIMP and coherent neutrino scattering from the Sun** with:
  - Recoil direction sensitivity
  - keV-scale threshold (10 keV in the plots)
  - Full 3D fiducialization
  - TPCs distributed in 5 underground sites scattered around the globe

- 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)

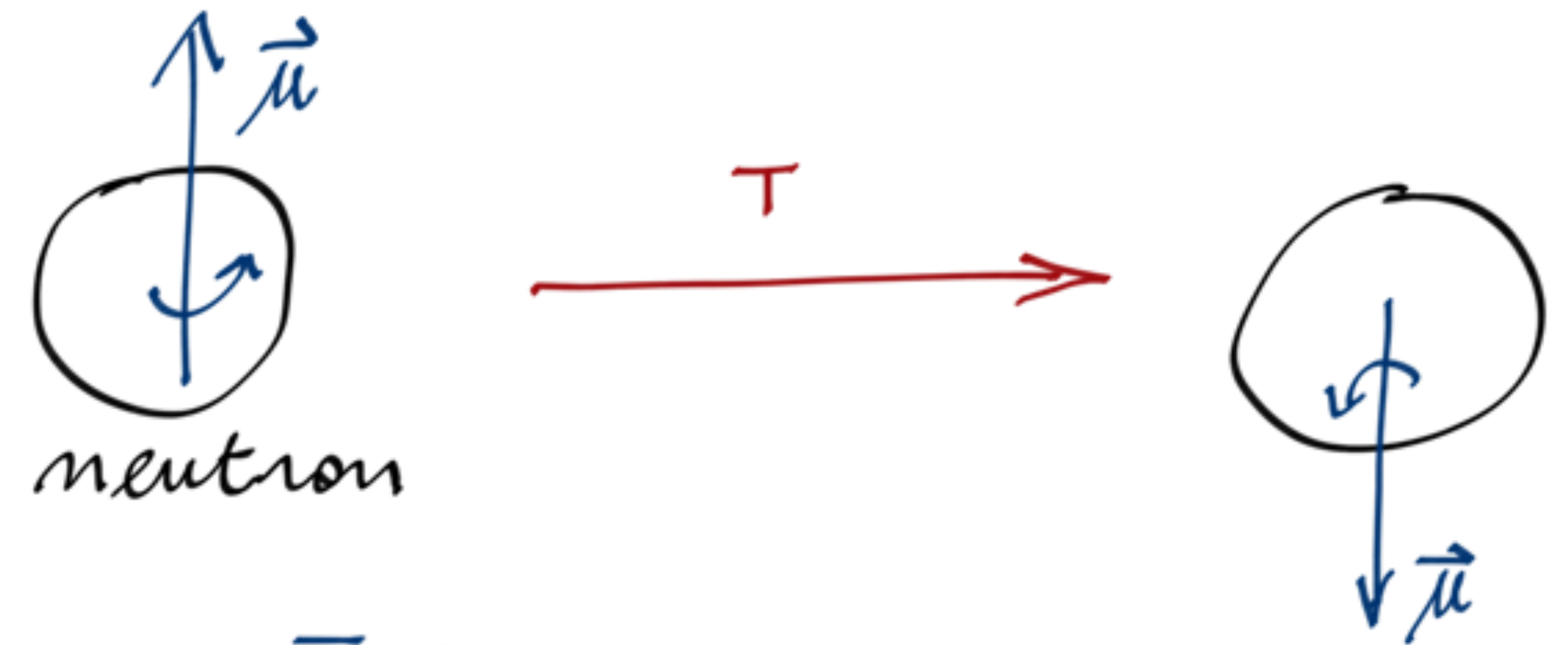
Building an international collaboration
from variois directional DM TPC groups to prepare LOI
DRIFT + NEWAGE + D³ + DMTPC + MIMAC + NITEC
UK + USA + Japan + Australia + <u>Italy</u>?

"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





AXION-LIKE PARTICLES
with sub THz photons



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

$\bar{\psi}\sigma^{ij}\psi \cdot \tilde{F}_{ij}$ CP-odd

$(\vec{\sigma}\cdot\vec{E})$

QCD action contains a CP odd term (euclidean)

$$i\,\theta\, q[A]$$

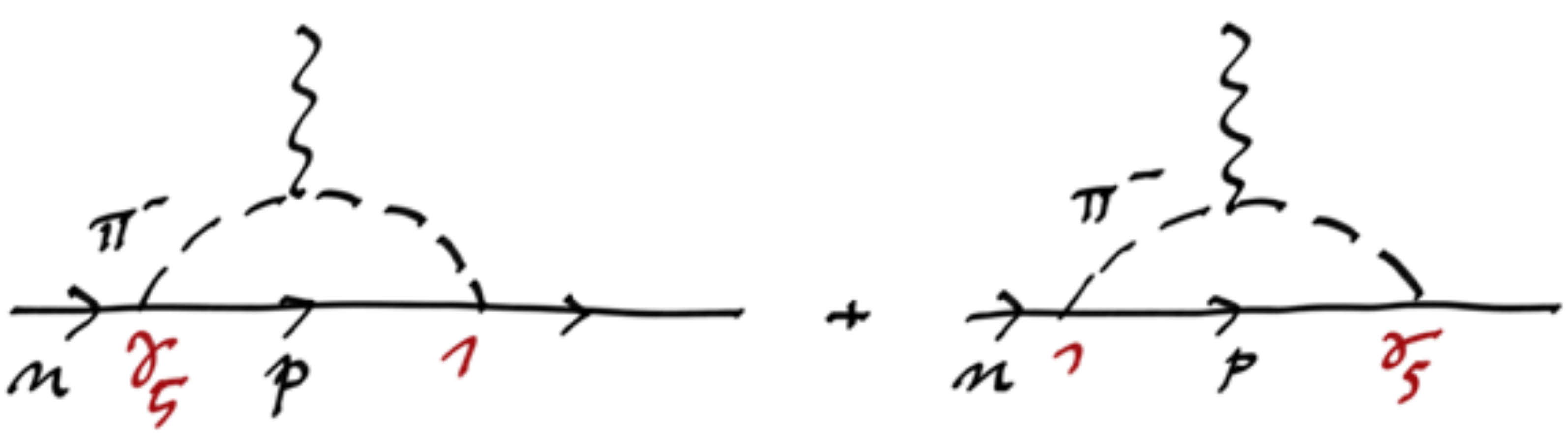
where

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

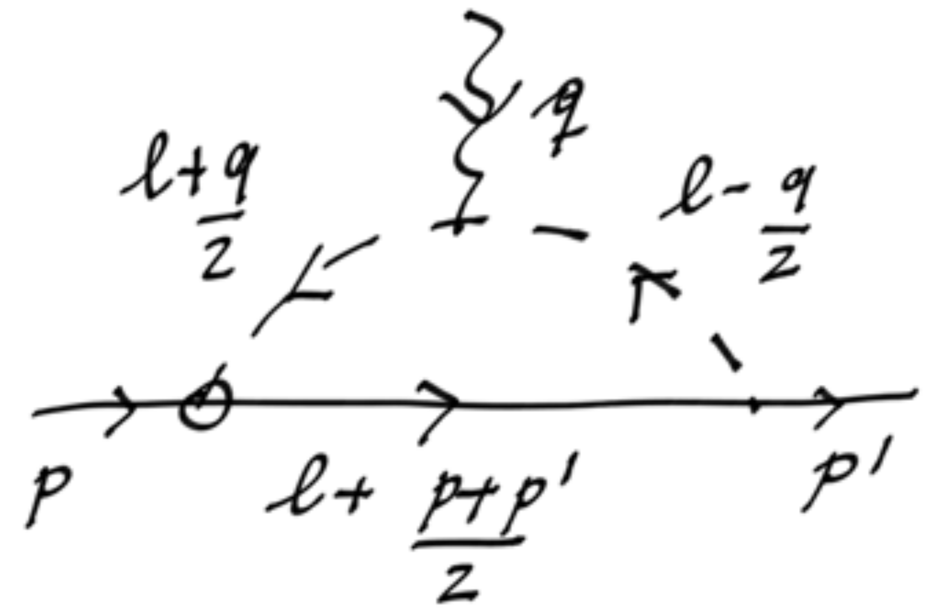
which induces a CP-odd term in the low energy theory

$$\mathcal{L}_{\pi NN} = g_{\pi NN}\, \bar{\Psi}\gamma_5 \vec{\sigma}\psi \cdot \vec{\pi} + g'_{\pi NN}\, \bar{\Psi}\vec{\sigma}\psi \cdot \vec{\pi}$$

Consider a gg' amplitude



separation of charge



$+ \ (\gamma_5 \leftrightarrow 1)$

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

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

$\gamma - \pi$ coupling ensures a $\ln \frac{\Lambda^2}{m_\pi^2}$ enhancement

where $\Lambda = 4\pi f_\pi$

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

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

Dependency on light quark masses

$$Z_\theta = N\int DA\, e^{-\frac{1}{4}(F,F) - i\theta q[A]} \int D\psi D\bar{\psi}\, e^{-(\bar{\psi},(\not{D}+M)\psi)-(\eta,\bar{\psi})-(\bar{\eta},\psi)}$$

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

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

However

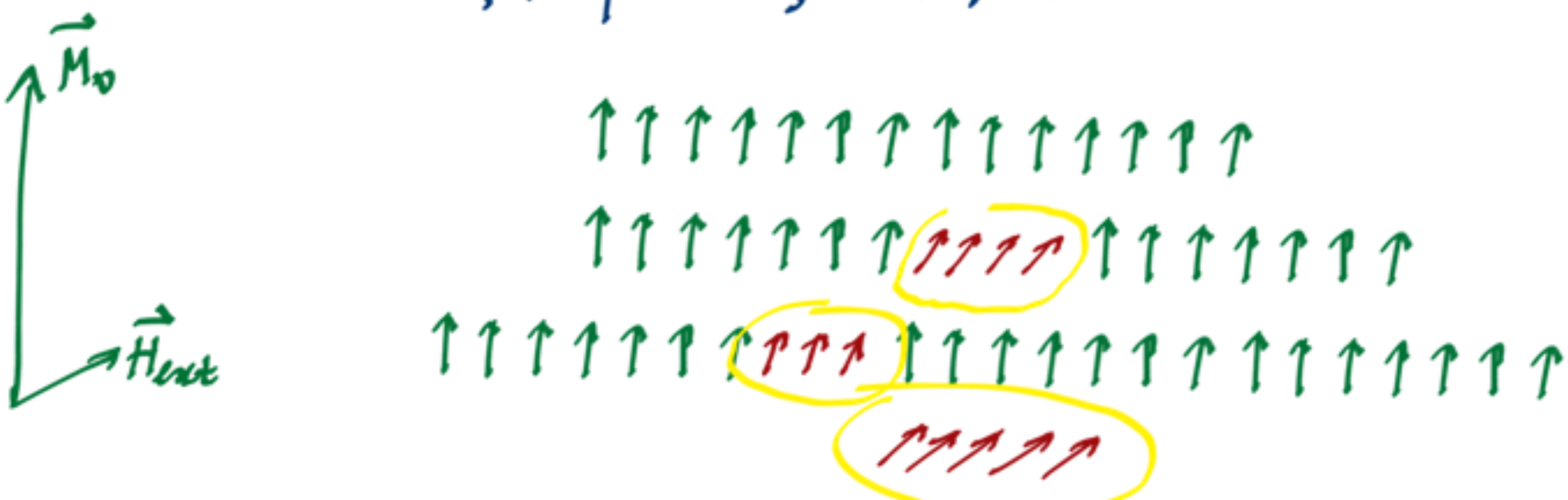
$$M \to M' = e^{-2i\alpha\gamma_5} M$$

So M' depends on θ, and

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

and require

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



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

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

Either $m_u \equiv 0$ or there is a dynamical reason setting $\theta \to 0$.

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

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

The minimum is at

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

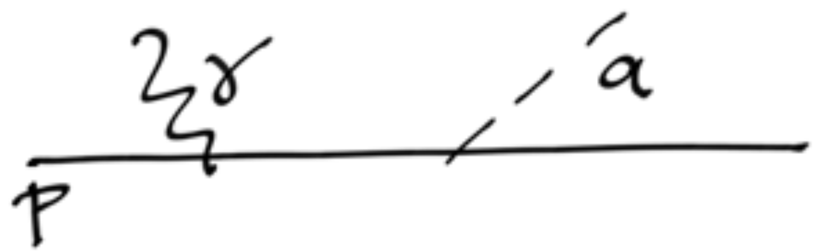
From the α^2 term one gets

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

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.



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

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

hydrogen

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

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

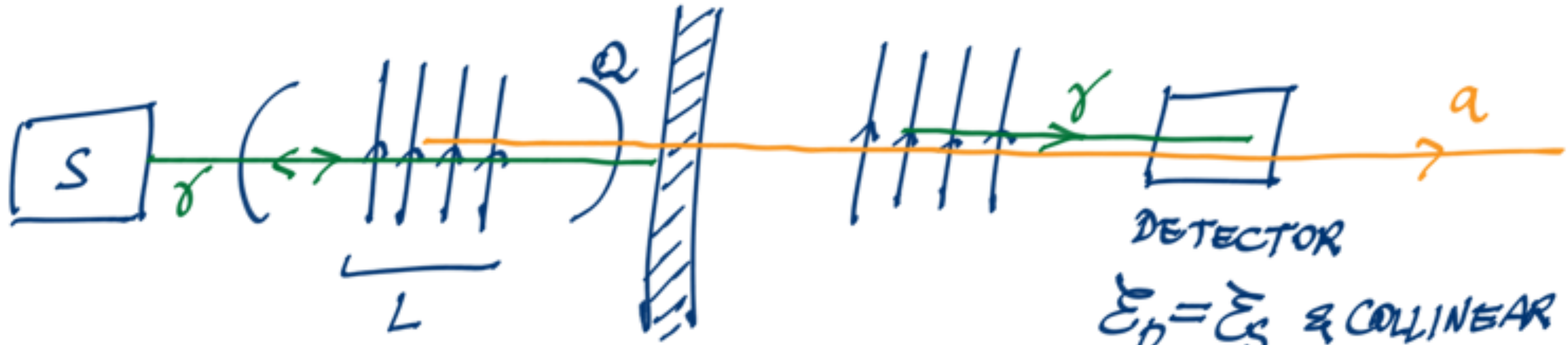
Require $R_\nu \sim R \rightarrow f \sim 10^{10}$ GeV. $m_a \simeq 2$ meV.

AXION–γ COUPLING

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

$$\underset{a}{T}(\pi^0 \to 2\gamma) = -\frac{1}{\underset{\to f}{f_\pi}}\frac{\alpha}{2\pi}\langle k_1 e_1\ k_2 e_2 | F\cdot\tilde{F} | \underset{a}{\pi^0} \rangle$$

LIGHT-SHINING-THROUGH-WALL



$\mathcal{E}_D = \mathcal{E}_S$ & COLLINEAR

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

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

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

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

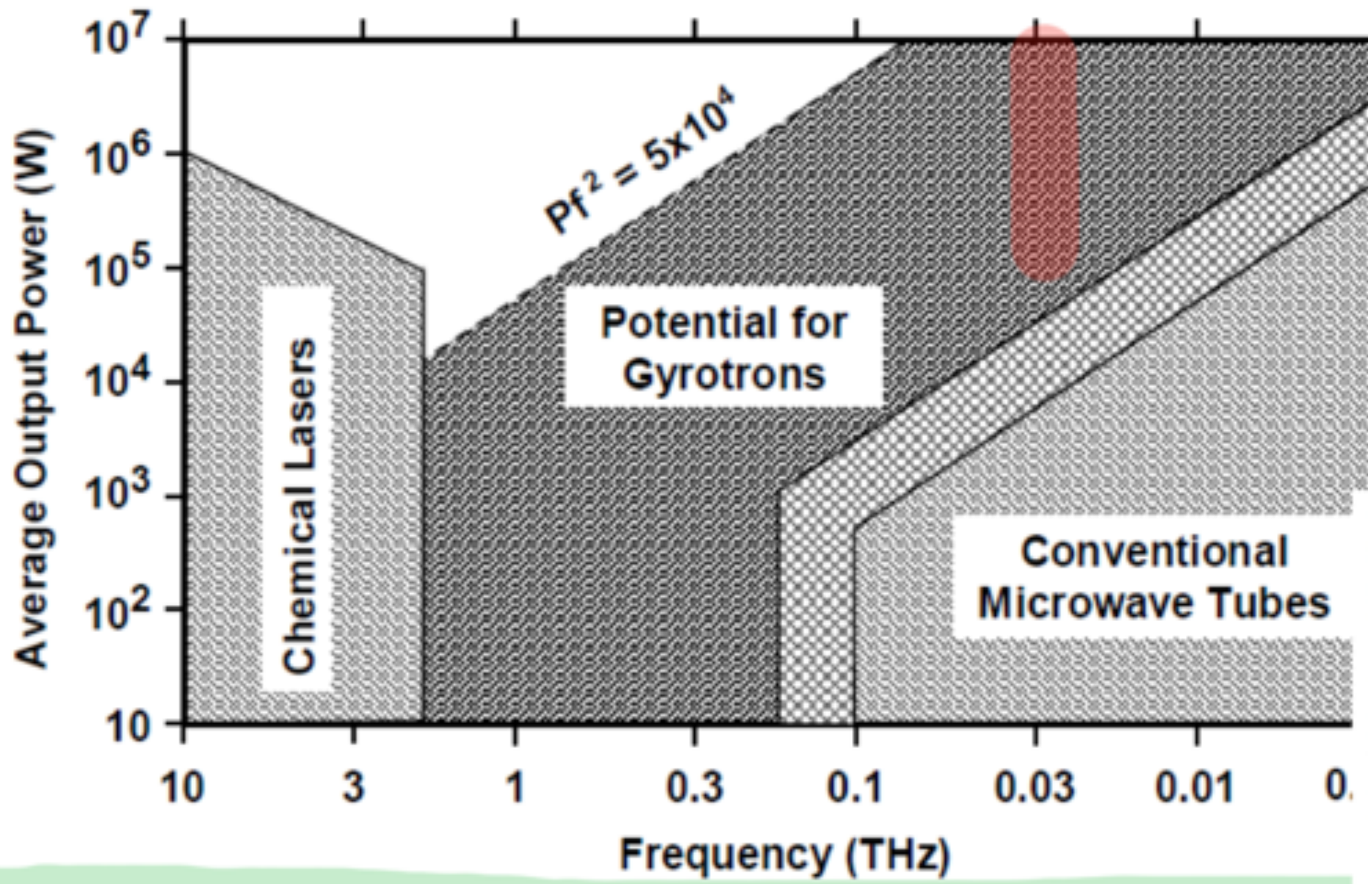
MEGAWATT GYROTRON SOURCES can produce (@30GHz)

$$\dot{N}_\gamma \simeq 10^{28}/\mathrm{sec}$$

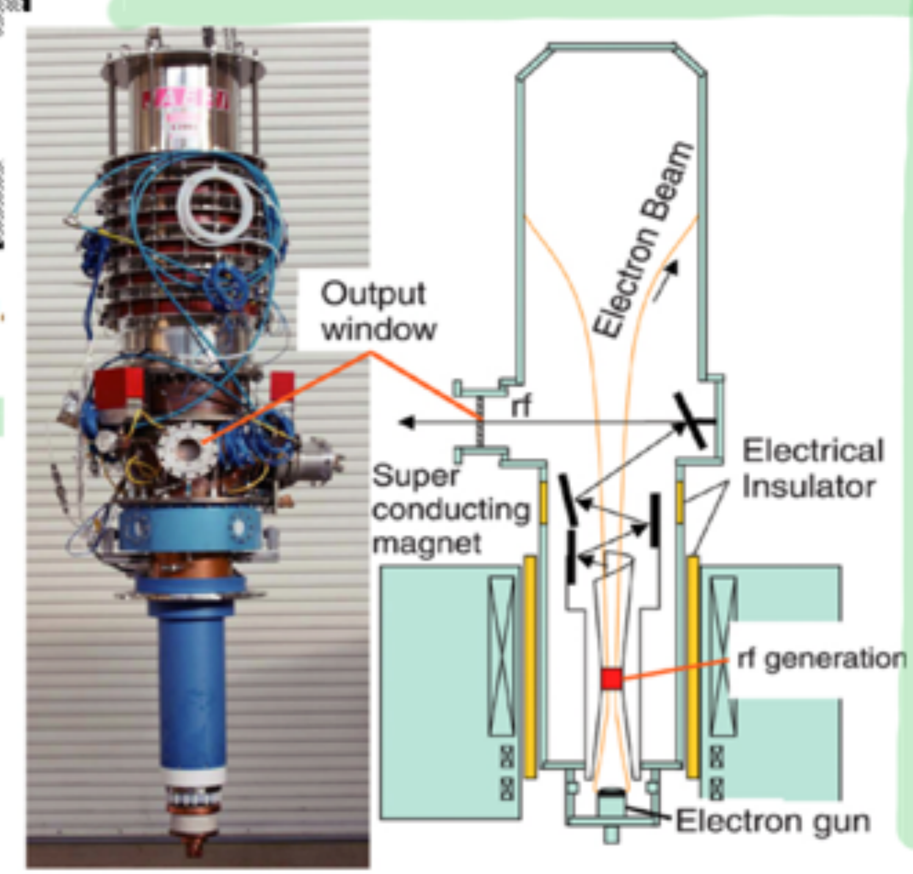
w/ continuous emission.

(10 LSW events/yr) × Q

Gyrotrons



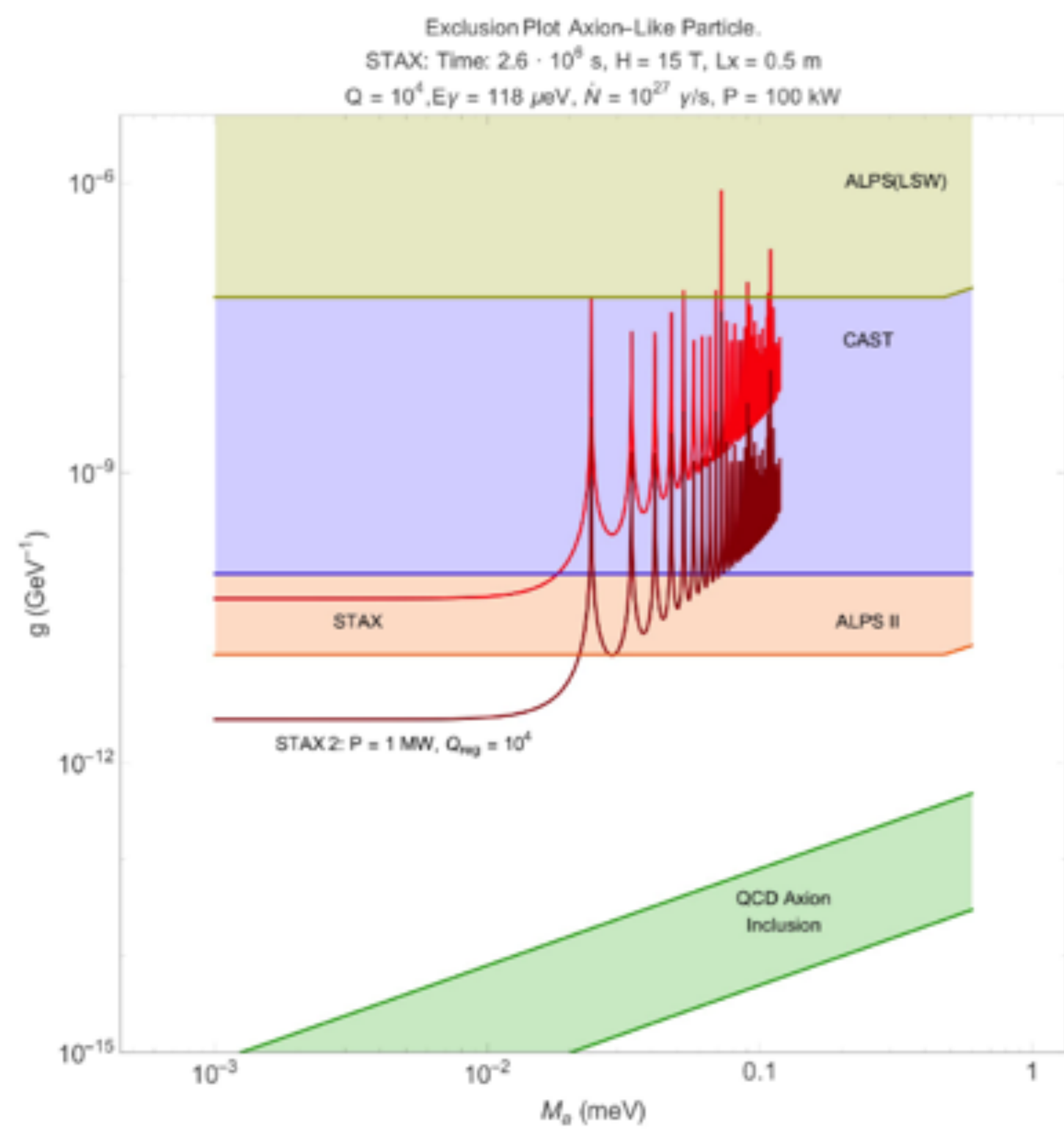
CW highly desired.



POTENTIAL REACH

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

$$q = E_\gamma - \sqrt{E_\gamma^2 - m_a^2} - 1/2L$$



EXCLUSION @ 90% CL

IN CASE OF A NULL RESULT

FOR AXIONS

$m_a \lesssim 0.02$ meV

ONE MONTH EXPOSURE

AND ZERO DARK COUNTS

STAX @ 100 KW

STAX2 @ 1 MW

+ REG. Q.

L. CAPPARELLI et al.

PHYS. DARK. UNIV. 12 (2016) 37

FABRY-PEROT CAVITIES

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

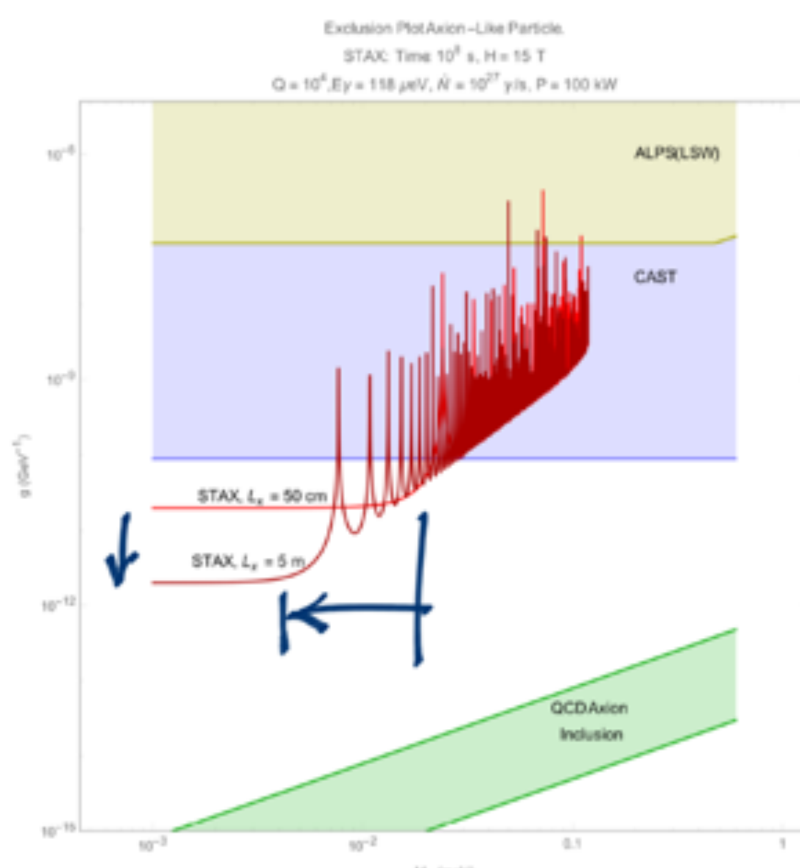
$$\downarrow$$

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

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

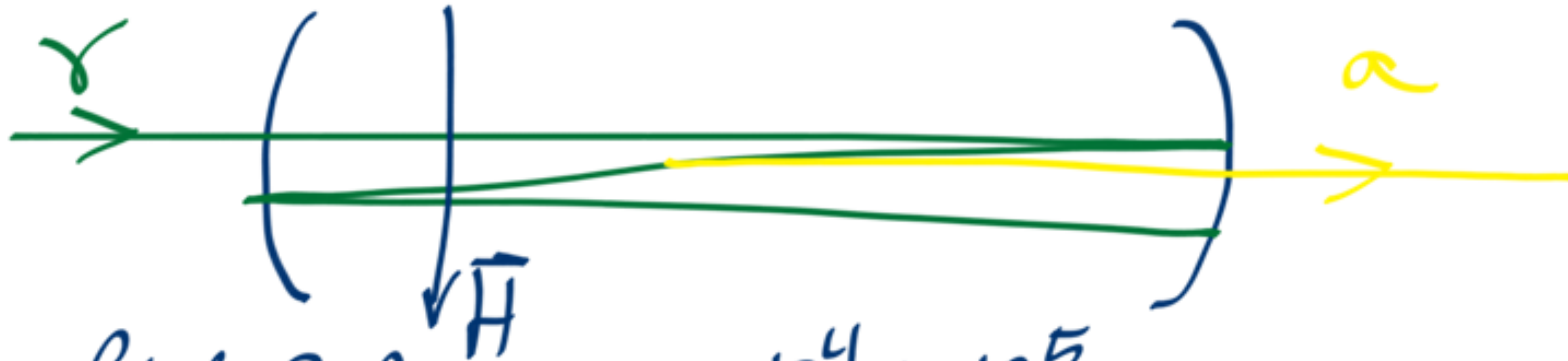
Someone suggests $Q^{-1/2}$ by setting a 'regeneration' cavity.

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



Some Numbers

Improvements are possible w/ FP cavities



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

Parameter	ALPS	STAX	g_{ALPS} / g_{STAX}	STAX II	g_{ALPS} / g_{STAXII}
Laser Power	0.8 W	100 kW	18.8	1 MW	188
Photon Energy	2.327 eV	124 μeV	11.7	124 μeV	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	$1.8\ 10^{-3}$ sec^{-1}	10^{-9} sec^{-1}	34.0	10^{-9} sec^{-1}	34
Combined Improvement			$\sim 10^4$		$\sim 8\times10^5$

TES

TES work @ T slightly below T_c.

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

$1\gamma\,(30\,\mathrm{GHz}) \rightarrow \Delta T_e \approx 40\,\mathrm{mK}$

Estimate & engineer ΔI –

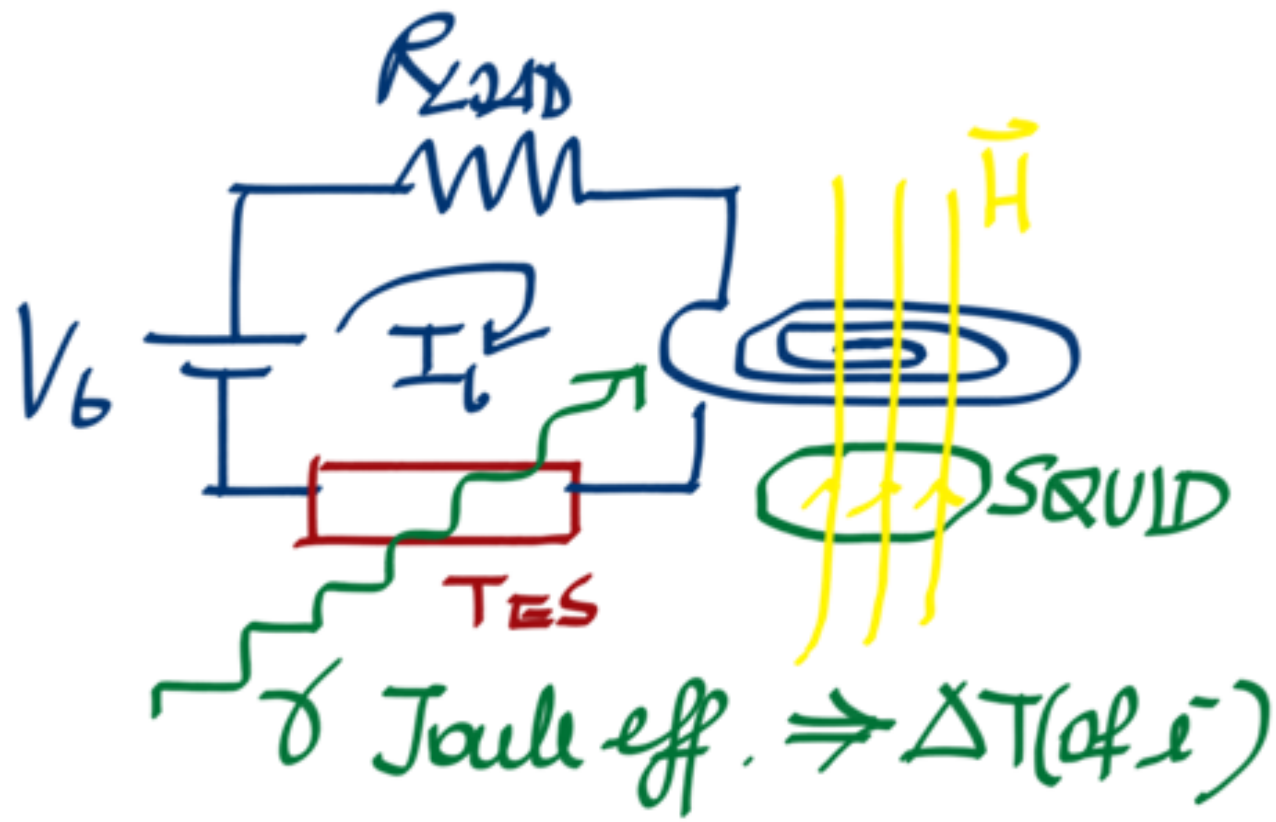
– SQUID SPECTRAL NOISE DENSITY

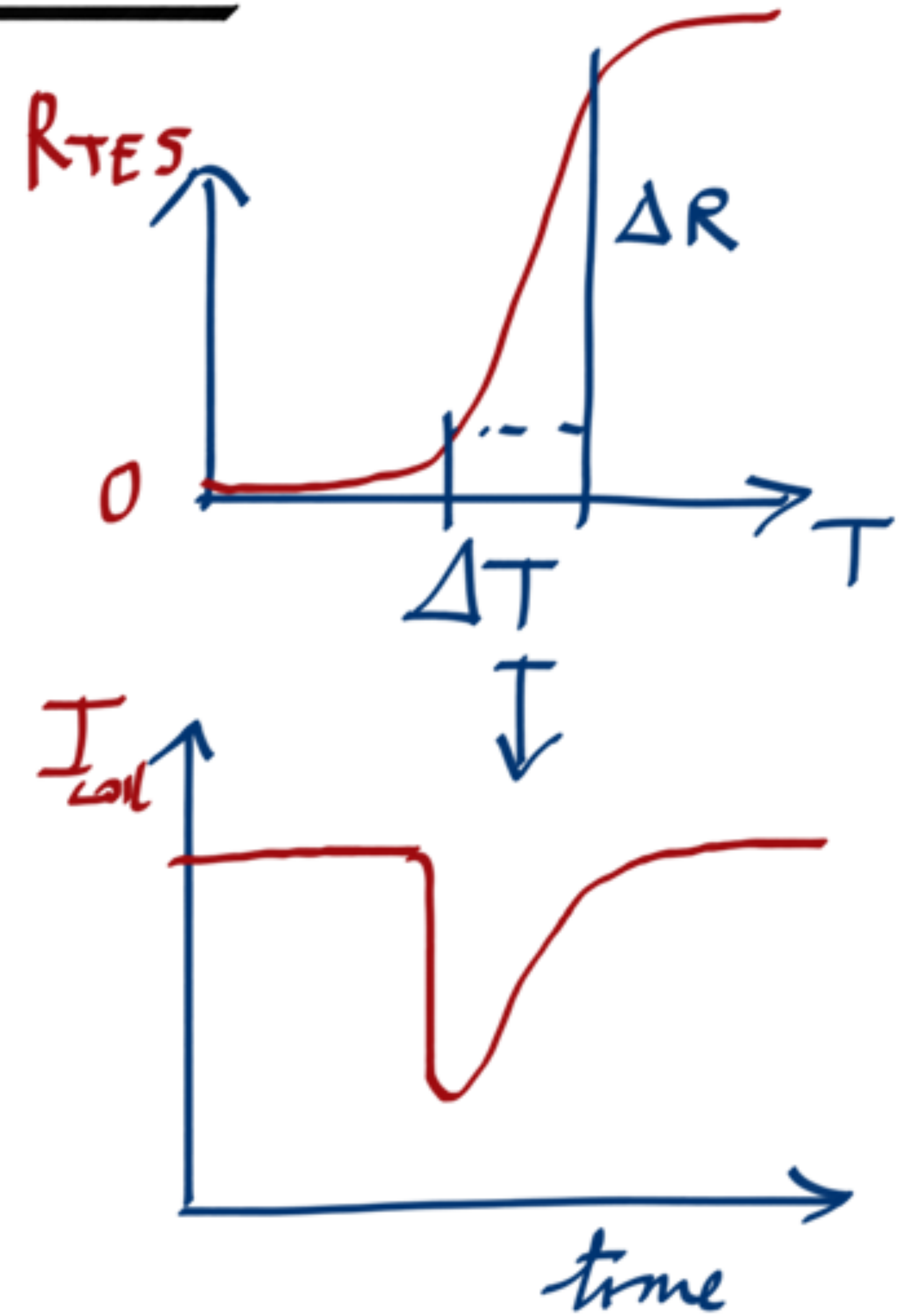
$$\frac{1\,\mathrm{pA}}{\sqrt{\mathrm{Hz}}}$$

– to be multiplied by the det. passband$^{1/2}$

$$\approx \sqrt{100\,\mathrm{Hz}}$$

EYE SCHEME





$\tau(e-\phi\ @\ 10\,\mathrm{mK}) \gtrsim 0.1\,\mathrm{sec}$

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.

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

Shifts the onset of oscillations to higher m_a values.

Example (CAST)

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

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

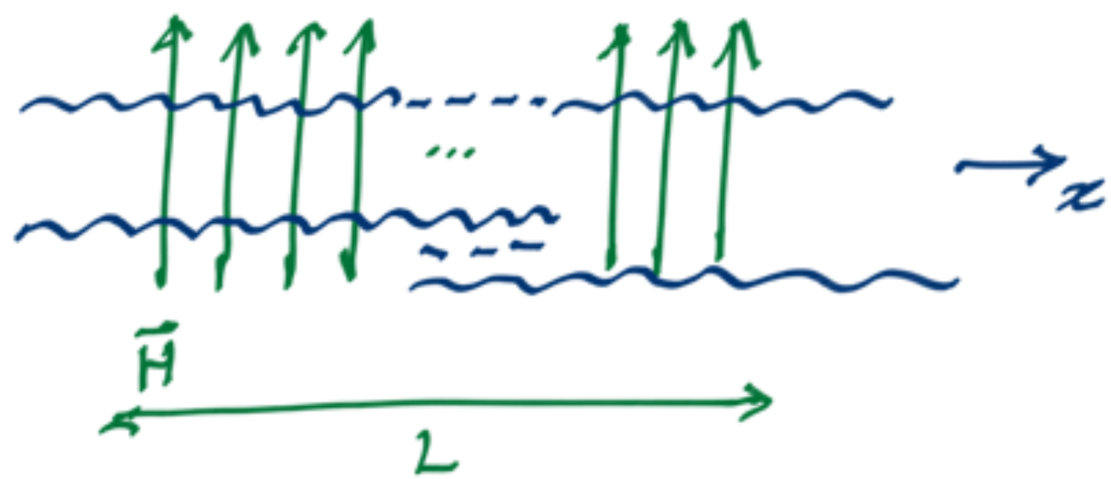
WIMPS & CNTs (DeCANT)

LM CAPPARELLI (UCLA)
G CAVOTO (INFN ROMA)
F COCINA (SAPIENZA)
J FERRETTI (INFN ROMA)
D MAZZILLI (SAPIENZA)
ADP (SAPIENZA)

AXIONS & SUB-THz γs (STAX)

LM CAPPARELLI (UCLA)
G CAVOTO (INFN ROMA)
J FERRETTI (INFN ROMA)
F GIAZOTTO (SNS & NEST)
ADP (SAPIENZA)
P SPAGNOLO (INFN PISA)

APPENDIX



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

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

$$q_1 = \mathcal{E}_\gamma + p^* \qquad i\epsilon \leftarrow i\epsilon p^* - \epsilon^2$$

$$q_2 = \mathcal{E}_\gamma - p^*$$

$$p^* = \sqrt{\mathcal{E}_\gamma^2 - m_a^2} > 0$$

Do integral in the complex plane, take its 'Im' part and get the standard formule

APPENDIX

$$P = G^2 H^2 \frac{\mathcal{E}_\gamma}{\sqrt{\mathcal{E}_\gamma^2 - m_a^2}} \left(\frac{\sin^2(q_2 L/2)}{q_2^2} + (2 \to 1) \right)$$

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

FWD a's $\quad q < \mathcal{E}_\gamma - \frac{1}{2L}$

from $p = k - q$

BKWD a's $\quad q > \mathcal{E}_\gamma + \frac{1}{2L}$

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

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