Title: Directional Light Dark Matter Detection

Date: Jun 19, 2018 01:30 PM

URL: http://pirsa.org/18060043

Abstract:

Directional detection of light Dark Matter

AD Polosa
Sapienza University of Rome

- Review of the WIMP
- Detection of WIMPs
- Directionality
- Carbon Nanotubes and ion channeling
- Review of the SIMP
- Electron recoils from graphene and carbon nanotubes
- Axion-Like particles and the (microwave) light-shining-through-wall detection scheme
- Concluding remarks

WIMP review

Dark Matter
left-over-Particles

- TO SURVIVE TO THE PRESENT THEY SHOULD CARRY A CONSERVED MULTIPLICATIVE OR ADDITIVE QUANTUM NUMBER.

- EVEN IF THE INITIAL NUMBER DENSITIES OF PARTICLES AND ANTIPARTICLES WERE EQUAL AND IF THEY CAN ANNIHILATE, THE EXPANSION RATE OF THE UNIVERSE CAN STOP THE DEPLETION PROCESS. AT SOME POINT THE NUMBER DENSITIES BECOME SUFFICIENTY LOW AND MAKE THE COLLISION RATE TOO LOW TO APPRECIABLY REDUCE THEM FURTHER.

Leftover particles

n = number density of dark matter particles χ

$$\chi\bar{\chi} \longrightarrow SM$$

The rate of decrease per particle

$$n\langle v\sigma\rangle_T = \Gamma$$

The rate of decrease IN THE NUMBER OF LEFTOVER PARTICLES IN A COMOVING VOLUME a^3

$$n a^3 \times n\langle v\sigma\rangle$$

[Lee & Weinberg PRD39, 165 (1977); DICUS, KOLB, TEPLITZ PRL39, 168 (1977)]

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Leftover particles

THE THERMAL BACKGROUND CREATES $\chi\bar{\chi}$ PAIRS (with a rate which is independent of n). At equilibrium

$$\chi\bar{\chi} \rightleftharpoons SM$$

Rate of decrease ~ Creation Rate ~

$$n_{EQ}^2 \, a^3 \langle \sigma v \rangle$$

$$\frac{d}{dt}(n a^3) = -\left(n^2 - n_{EQ}^2\right) a^3 \langle \sigma v \rangle$$

Leftover particles

If $k_B T \gg m_\chi$ then

$$n_{EQ} \sim T^3 \sim \left(\frac{1}{a}\right)^3 \qquad \text{[rel. particles]}$$

Thus, for $k_B T \gg m_\chi$, n_{EQ} IS A SOLUTION OF THE BOLTZMANN EQ.

$$\frac{d}{dt} 1 = -\left(n_{EQ}^2 - n_{EQ}^2\right) a^3 \langle \sigma v \rangle = 0$$

But when the temperature drops to $k_B T \ll m_\chi$ the creation term is Gibbs suppressed

$$\frac{d}{dt} n a^3 = - n^2 a^3 \langle \sigma v \rangle$$

Leftover particles

If $k_B T \gg m_\chi$ then

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But when the temperature drops to $\underline{k_B T \ll m_\chi}$ the creation term is Gibbs suppressed

$$\frac{d}{dt} n a^3 = - n^2 a^3 \langle \sigma v \rangle$$

Leftover particles

$$\frac{d}{dt} n a^3 = -(n a^3)^2 \frac{\langle \sigma v \rangle}{a^3}$$

$$n(t) a^3(t) = \frac{n(t_1)\, a^3(t_1)}{1 + n(t_1)\, a^3(t_1) \int_{t_1}^{t} \frac{\langle \sigma v \rangle}{a^3(t')} dt'}$$

THE INTEGRAL IS CONVERGENT FOR LARGE t → there are left over particles.

Reformulate the Boltzmann equation exchanging

$$t \rightarrow T$$

Leftover particles

DURING THE PERIOD OF THERMAL EQUILIBRIUM THE VARIATION WITH TIME OF T IS GOVERNED BY

$$\begin{cases} s(T)\,a^3 = \text{const.} \\ \dfrac{\dot{a}^2}{a^2} = \dfrac{8\pi G_N \rho(T)}{3} \quad \text{(Friedmann)} \end{cases}$$

$$-\dot{T}\,\frac{s'(T)}{s(T)} = 3\,\frac{\dot{a}}{a} = \sqrt{24\pi G_N \rho(T)}$$

$$t = -\int \frac{s'(T)}{s(T)} \frac{dT}{\sqrt{24\pi G_N \rho(T)}} + \text{cost.}$$

[rel. ideal. gas] $\quad s(T) = \dfrac{2\mathcal{N} a_B T^3}{3}, \quad \rho(T) = \dfrac{\mathcal{N} a_B T^4}{2}, \quad \mathcal{N} = \#\text{ d.o.f.}$

WIMPs

$$\boxed{\frac{d}{dx}\mu(x) = B\left[\mu^2(x) - \mu_{EQ}^2(x)\right] \quad \text{(Riccati Eq.)}}$$

$$x \equiv \frac{k_B T}{m_\chi} \qquad \mu \equiv \frac{n}{(k_B T)^3} \quad \text{(dimensionless)}$$

$$B = \sqrt{\frac{45}{4\pi^3 G_N N}} \langle \sigma v \rangle m_\chi$$

$$\langle v \sigma \rangle_T \sim G_F^2 m_\chi^2 \frac{F}{2\pi} \sim \text{const}$$

WIMPs

The fudge factor $\mathcal{F}$ counts the # of annih. channels and rescales G_F

$$\mathcal{F} \sim \frac{M_W^4}{\tilde{M}^4}$$

depending on the model. The present density of leftover parts.

$$\rho_\chi = \underbrace{2}_{\chi \,\&\, \bar{\chi}} m_\chi \underbrace{u(0)}_{T\sim 0} \left(k_B T_0\right)^3$$

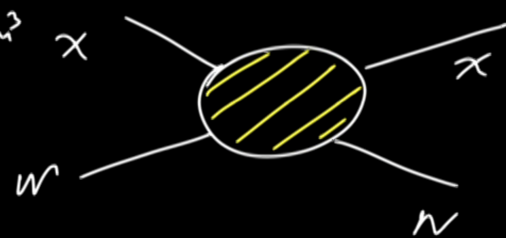
Requiring $\Omega_\chi = \dfrac{8\pi G_N \rho_\chi}{3H_0^2} \approx \Omega_M$ (and from $u(0) \simeq 6B^{-0.95}$)

$$\boxed{m_\chi \left(\frac{\mathcal{F}}{\sqrt{N}}\right)^{1/2} \simeq 3.7 \left(\underbrace{\Omega_M h^2}_{0.15}\right)^{-1/2} \text{GeV}}$$

Detect WIMPs

RECOIL OF ATOMIC NUCLEI FROM WHICH THEY SCATTER ELASTICALLY

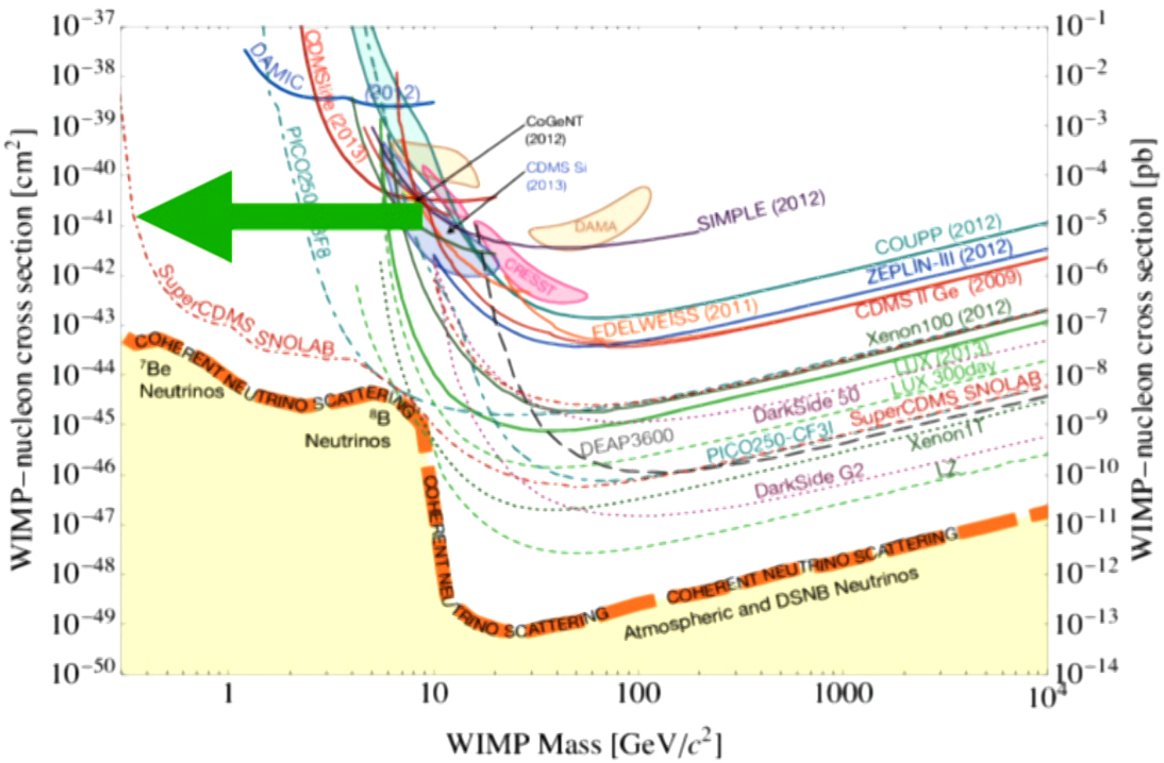
$$\begin{cases} v \approx 230\,\mathrm{km/sec} \\ \rho_\chi \approx 0.3\,\mathrm{GeV/cm^3} \end{cases}$$



ENERGY RELEASE IN A CRYSTAL, GAS, LIQUID

EXCLUSION PLOT

Light Dark Matter



See Alexander et al. 1608.08632
Dark Sectors Community Report

10/11/15

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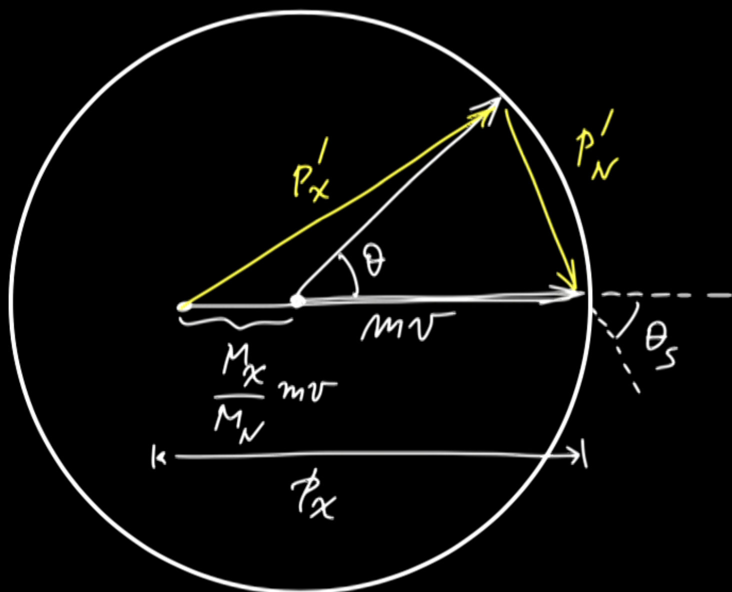
Wimps2

Wimp Kinematics

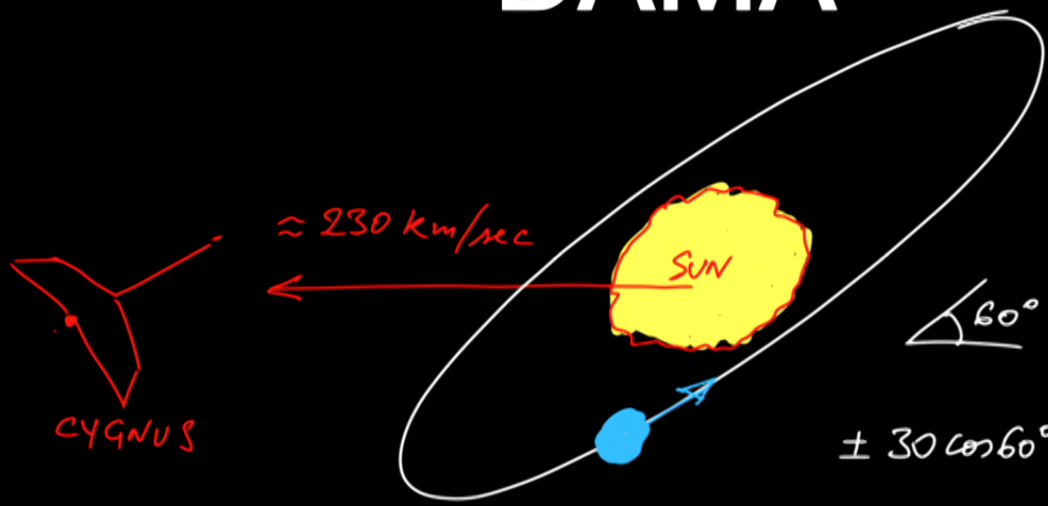


$M_\chi \sim M_N$

1) $T_N'^{\,max} = T_\chi$ (kinetic energy)

2) $\theta_s = 0$ (forward)

DAMA



$\pm 30 \cos 60°$ km/sec

$\longrightarrow$ SEASONAL MODULATION

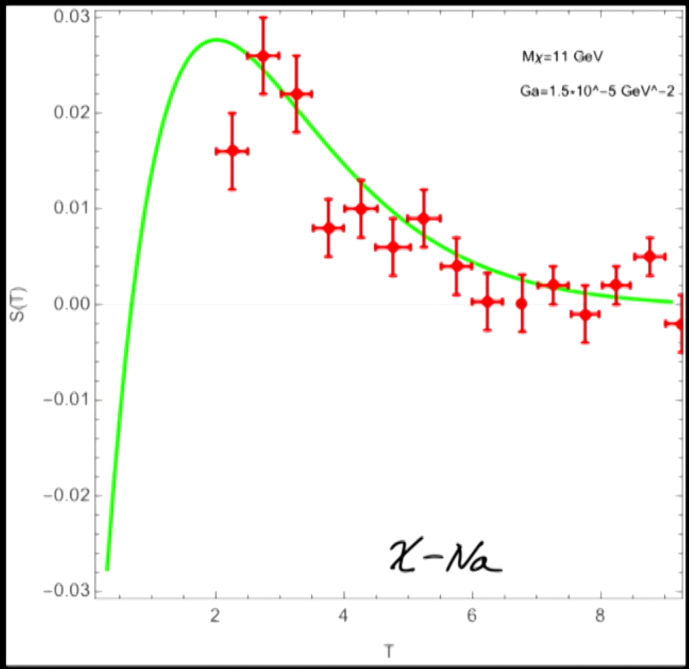
$$f(\vec{v}) = \beta\, e^{-\frac{(\vec{v}+\vec{w}(t))^2}{v_0^2}} \; ; \quad \vec{w}(t) = \left[232 + 15\cos\left(\frac{2\pi t}{365}+\varphi_0\right)\right]\hat{k}$$

km/sec.

$\beta \sim \frac{1}{v_0^3}$; $v_0 \approx 230$ km/sec.

DAMA

$$\left(\frac{cpd}{kg \cdot keV}\right)$$



$$\frac{d\Gamma}{dT'_N} = A(T'_N) + S(T'_N)\cos(\omega t + \varphi_0)$$

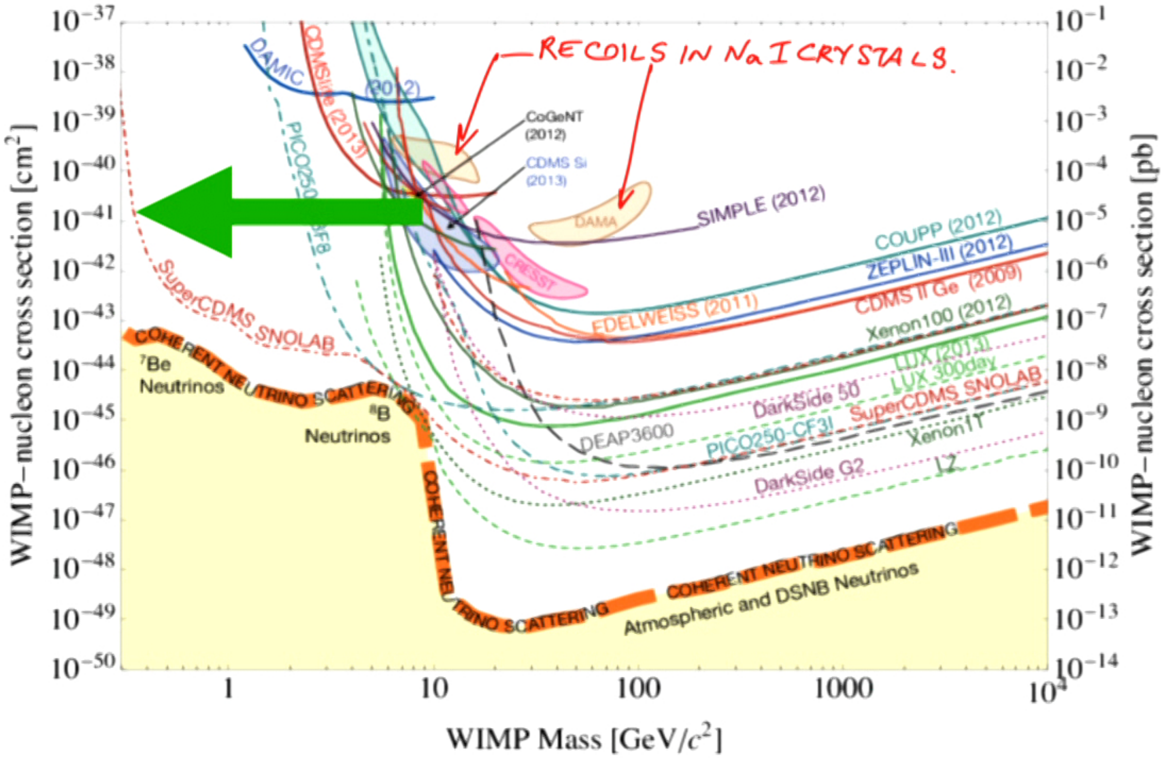
NUCLEAR RECOIL KINETIC ENERGY $= T'_N$ (KeVee)

[CAPPARELLI, CAVOTO, MAZZILLI, ADP Phys Dark Uni. 11 (2016) 79]

Directionality and carbon nanotubes

EXCLUSION PLOT

Light Dark Matter



See Alexander et al. 1608.08632
Dark Sectors Community Report

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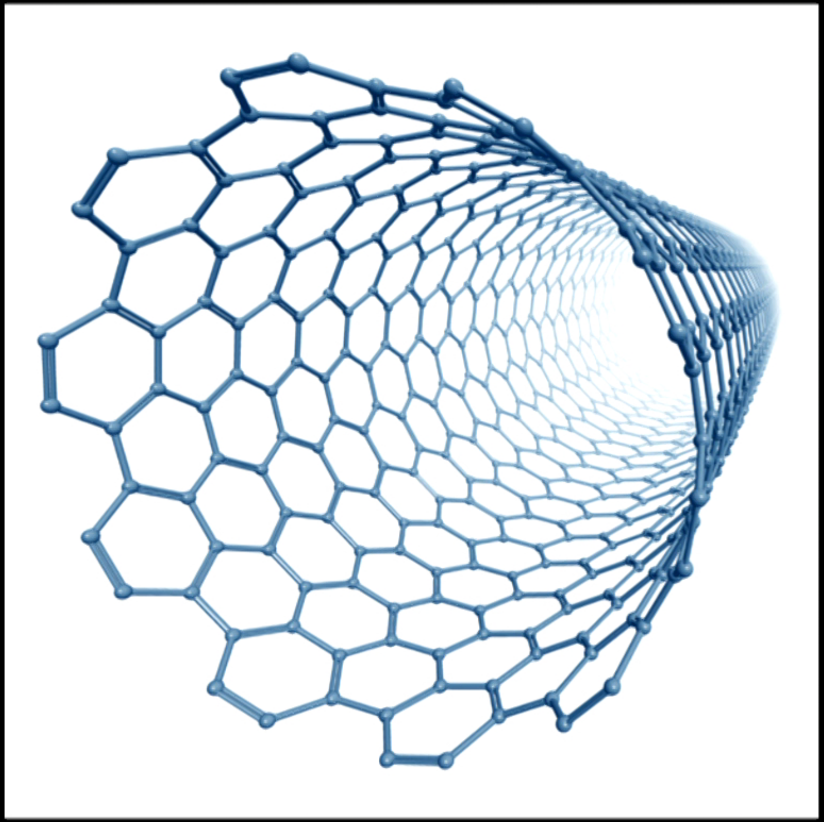
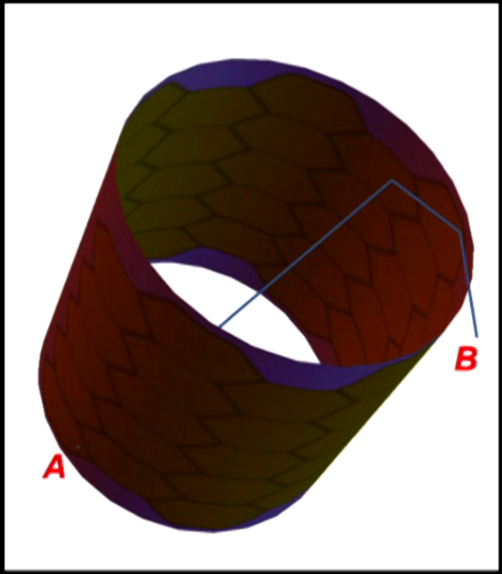
Wimps2

Carbon Nanotubes

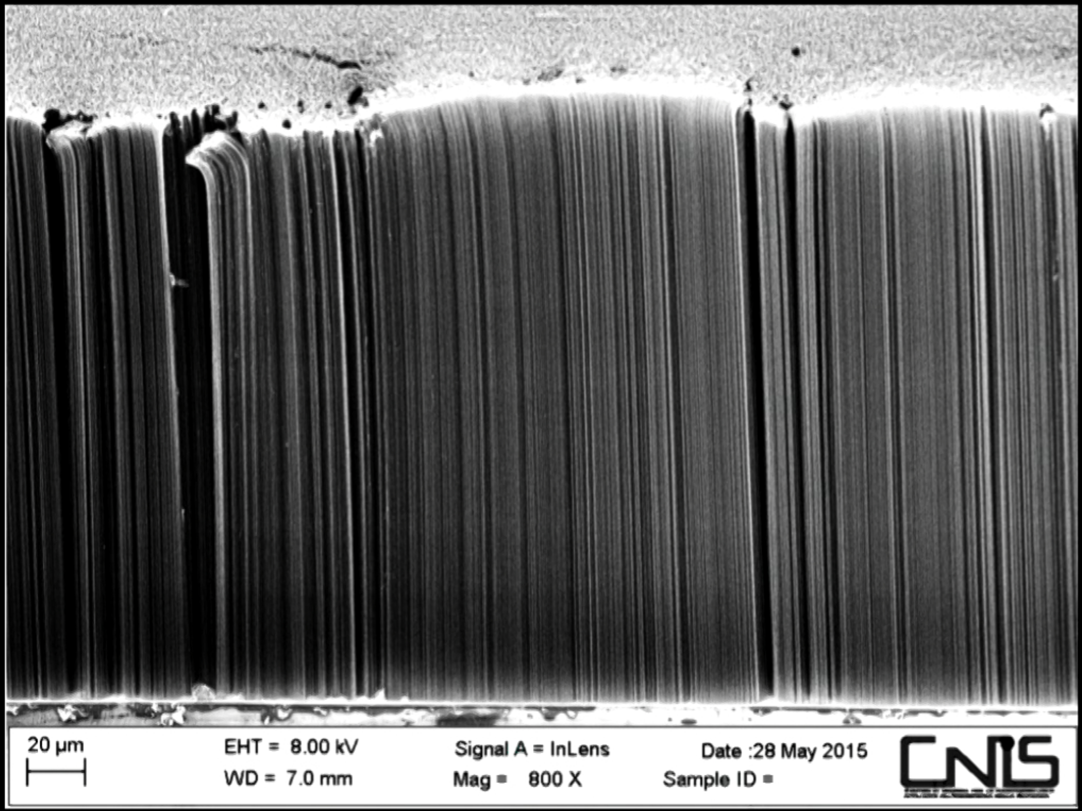


Directionality in CNTs

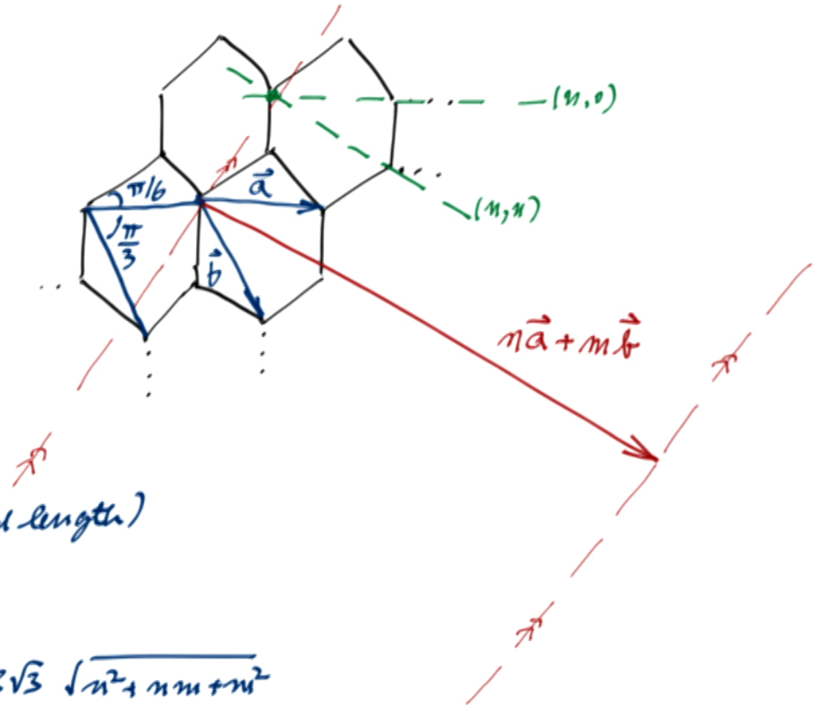


CAN CNT's BE GOOD CHANNELS FOR POSITIVE CARBON IONS INJECTED IN THEM BY A χ ALMOST COAXIAL W/ THE CNT?

CNT arrays


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

CNT Target



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

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

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

(n,n) "HARMCHAIR" – METALLIC

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

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

08/03/2016

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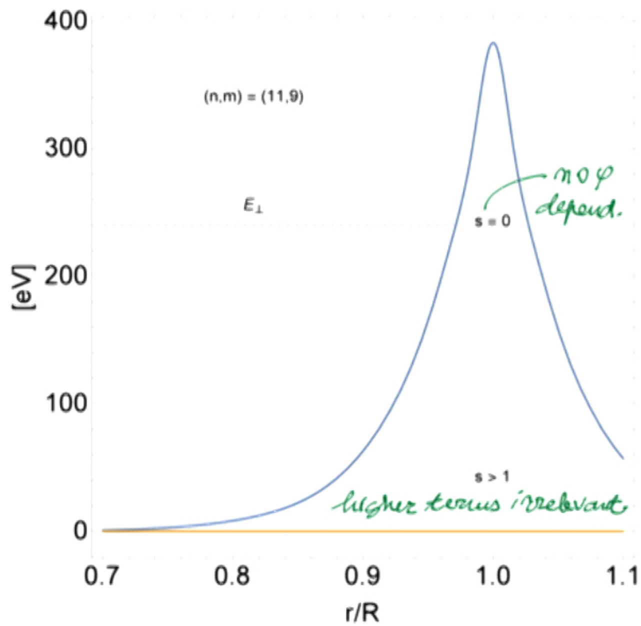
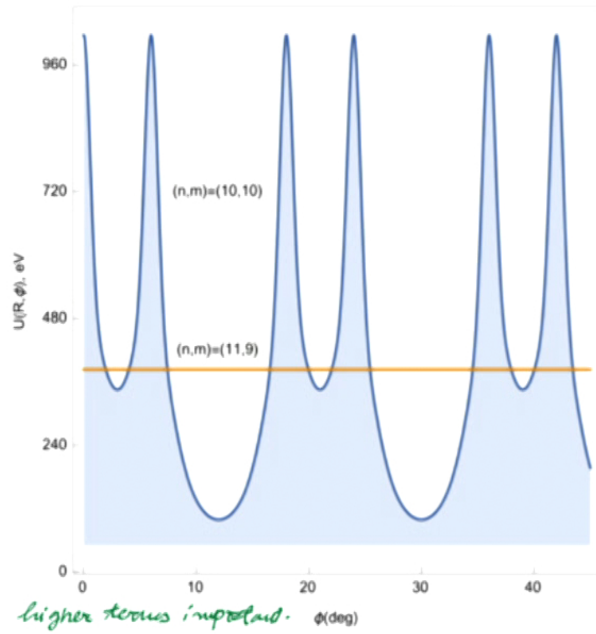
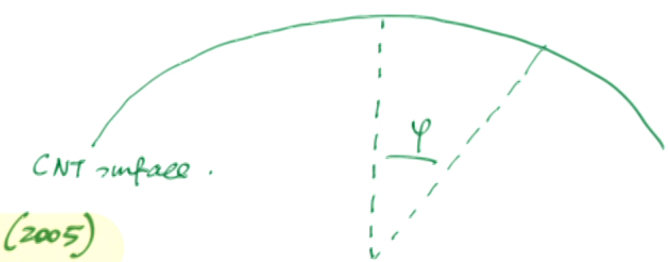
DM-Weizmann

CNT POTENTIALS





(For a C^{6+})



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

08/03/2016

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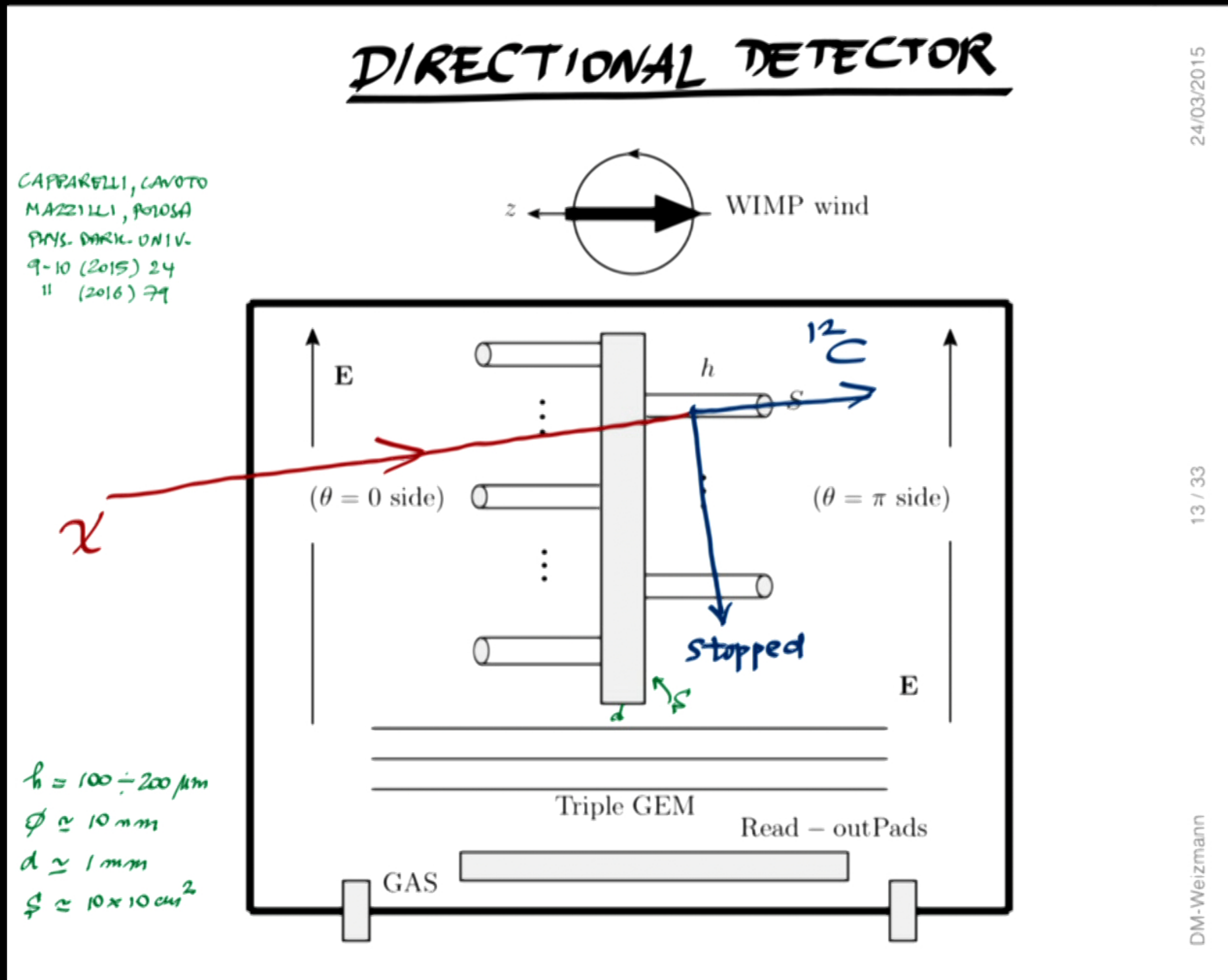
DM-Weizmann

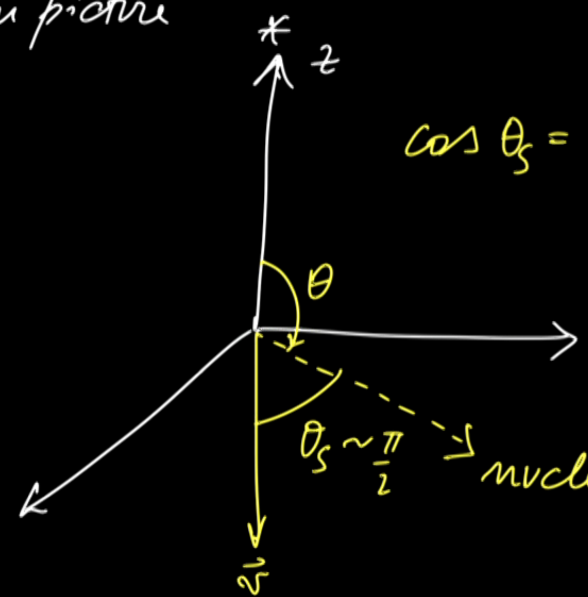

DIRECTIONAL DETECTOR
24/03/2015
CAPPARELLI, CAVOTO
MAZZILLI, POLOSA
PHYS. DARK. UNIV.
9-10 (2015) 24
11 (2016) 79
z
WIMP wind
E
h
S
^{12}C
χ
($\theta = 0$ side)
($\theta = \pi$ side)
13 / 33
stopped
E
d
$h = 100 \div 200\ \mu m$
$\phi \simeq 10\ mm$
$d \simeq 1\ mm$
$S \simeq 10 \times 10\ cm^2$
Triple GEM
Read − outPads
GAS
DM-Weizmann

Nuclear Recoils

If we consider recoils with $T'_N \to 0$, that means $\theta_S \to \frac{\pi}{2}$.

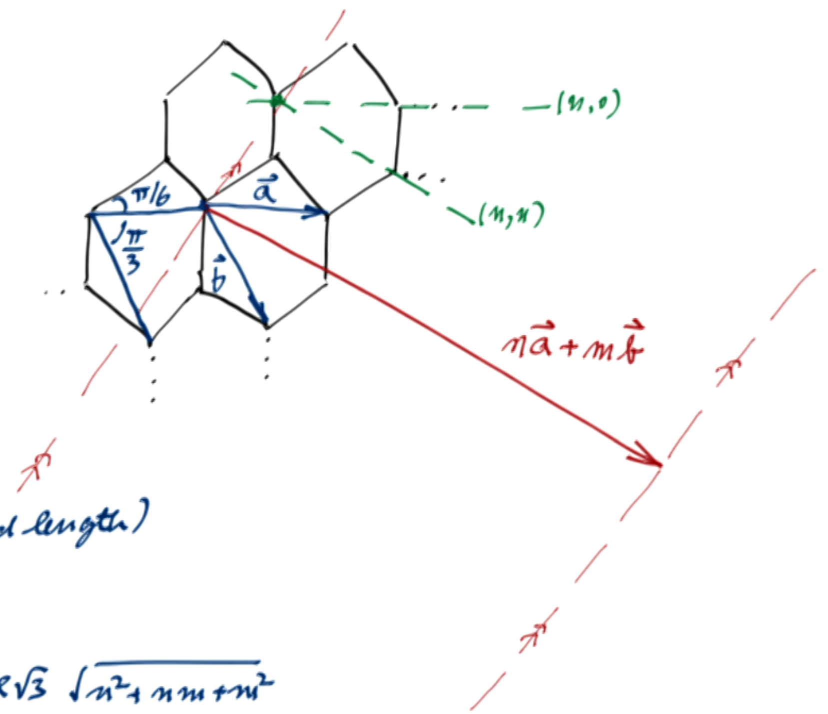
Take $\vec{v}$ as in picture

$$\cos\theta_S = \sqrt{\frac{T'_N}{\mu v^2}}$$



As T'_N is increased we expect recoils at larger θ values

CNT Target



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

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

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

(n, n) "HARMCHAIR" – METALLIC
(n, m) with (n−m) multiple of 3 – SEMICONDUCT.
(n, 0) "ZIG-ZAG"

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 ~ 147 eV
C^{5+} " ~ 539 eV
C^{6+} " ~ 1029 eV

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

10/03/16

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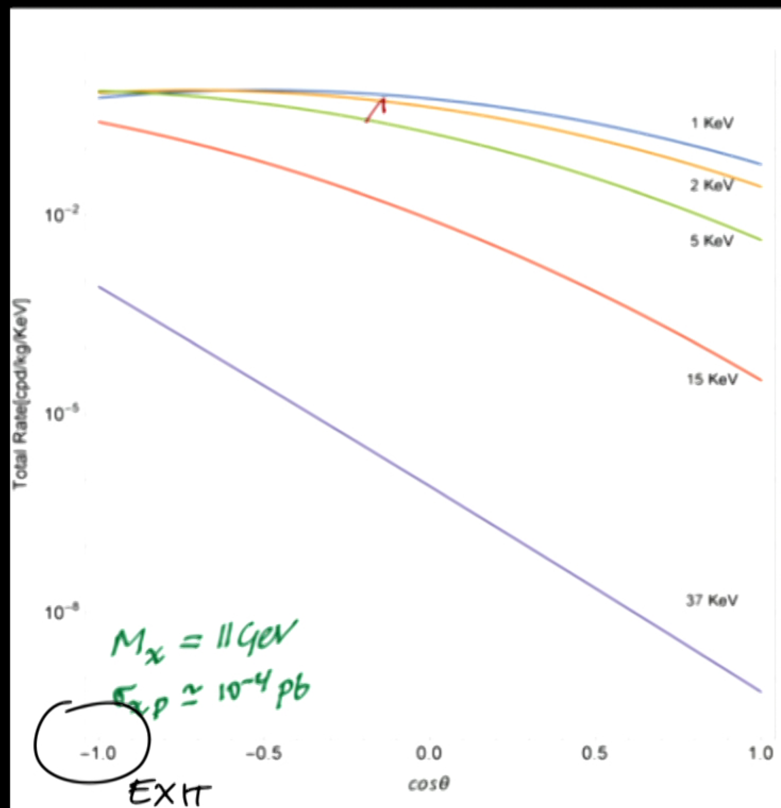
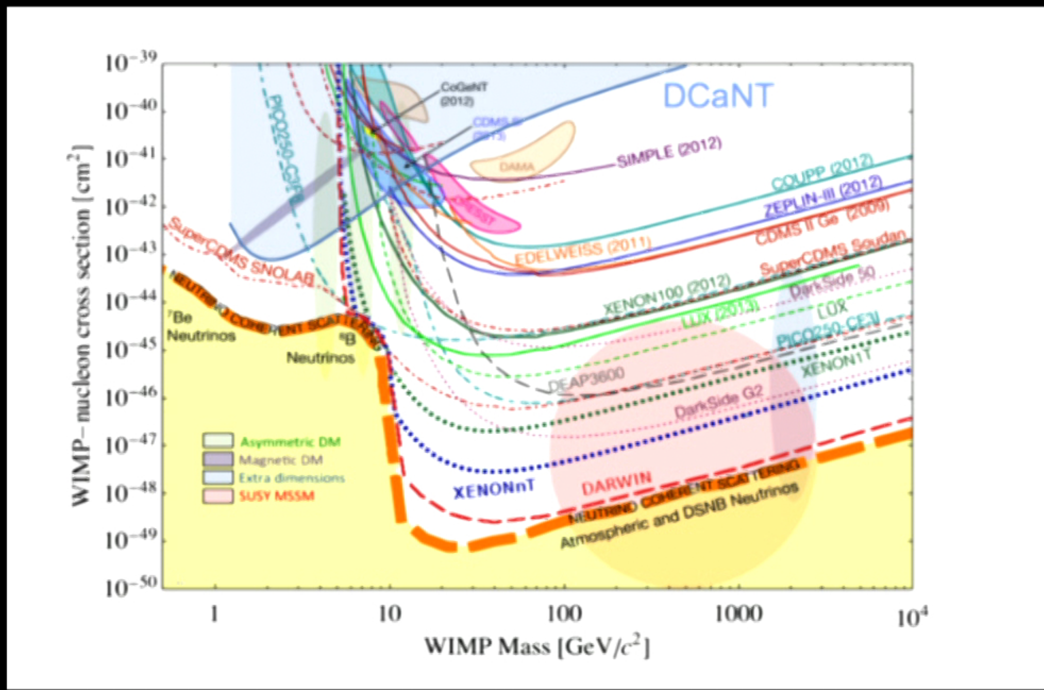
Wimps2

Nuclear Recoils

GENERATE
MC NUCLEAR
TRAJECTORIES
WITH T'_N FROM
$\frac{d\Gamma}{dT'_N}$ DISTRIB.

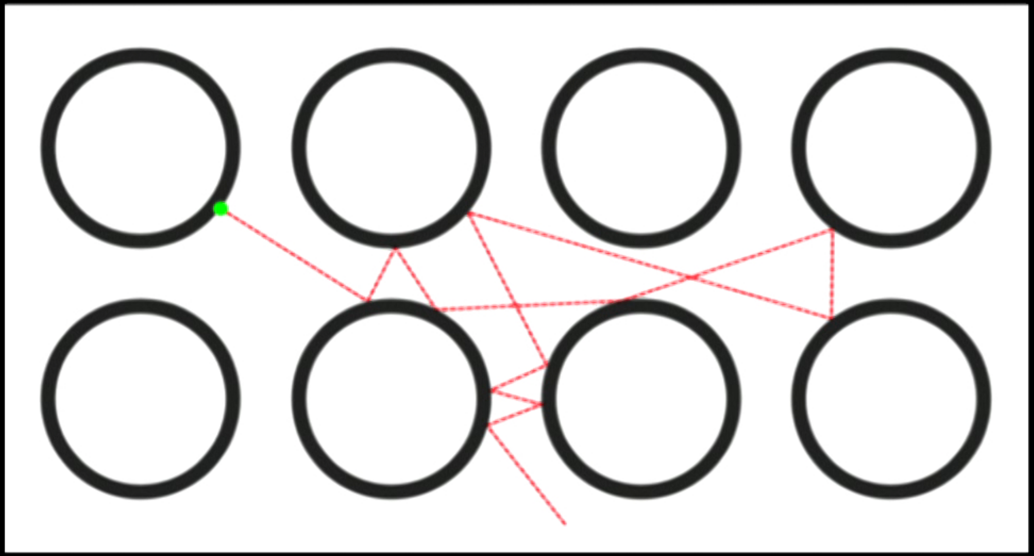


Sensitivity



- 100 layers, 1 m^2 each
- Cygnus tracking system
- detection of out ions @ 1 keV
- Sensitivity for 0.4 kg · year.

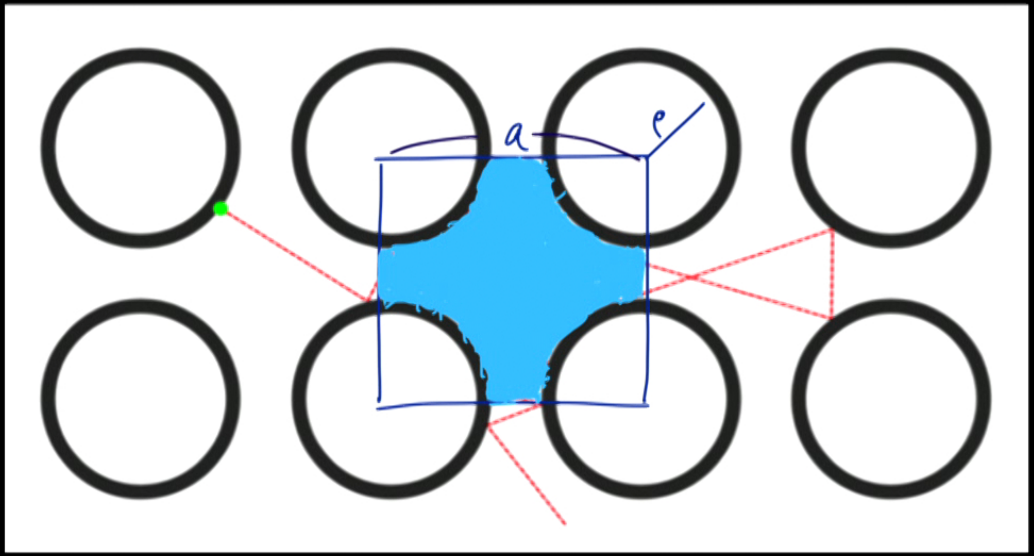
Billiards



IF THE ION ENTERS THE CNT FOREST WITH $(v_{\parallel}, v_{\perp})$ WILL IT REACH THE TOP, WHERE IS DETECTED, BEFORE EXITING FROM SIDES?

[CIRILLO, CAVOTO, COCINA, FERRETTI, ADP EPJC (2016) 76]

Billiards

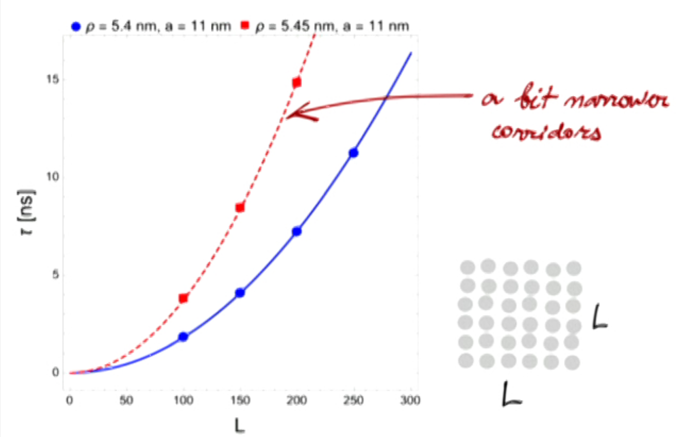


$$\tau_R = \frac{\pi(a^2 - \pi\rho^2)}{4v_\perp(a-2\rho)} = \text{time in shaded area}$$

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

[CIRILLO, CAVOTO, COCINA, FERRETTI, ADP EPJC (2016) 76]

Billiards

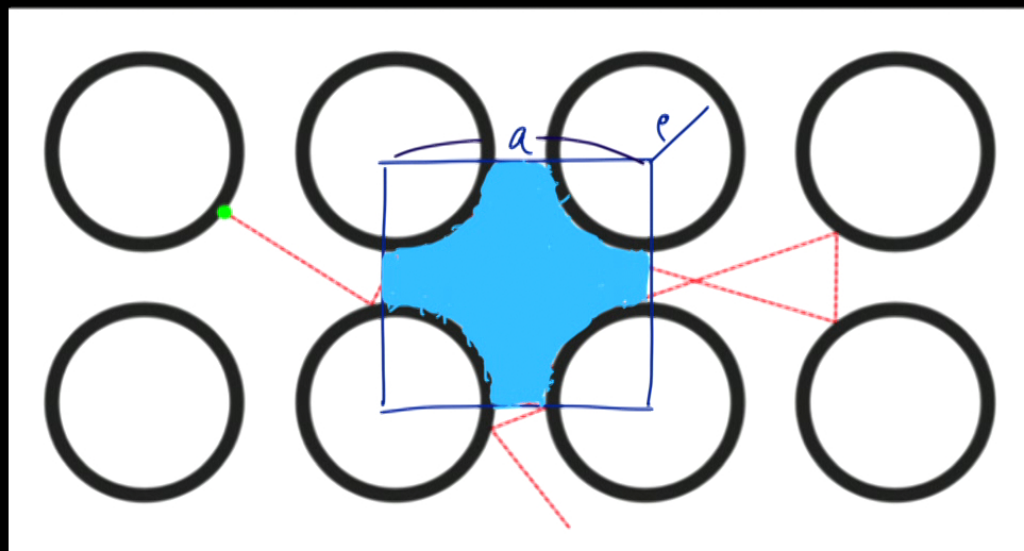


find $n_h \simeq \frac{L^2}{7}$; $E_\perp \simeq 300\,eV$

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

WE FOUND 1) LATERAL LOSSES ARE PERFECTLY NEGLIGIBLE especially when compared to the softening of the ion energy in the channel.
2) INTERSTICES ARE MORE IMPORTANT THAN TUBES

Billiards



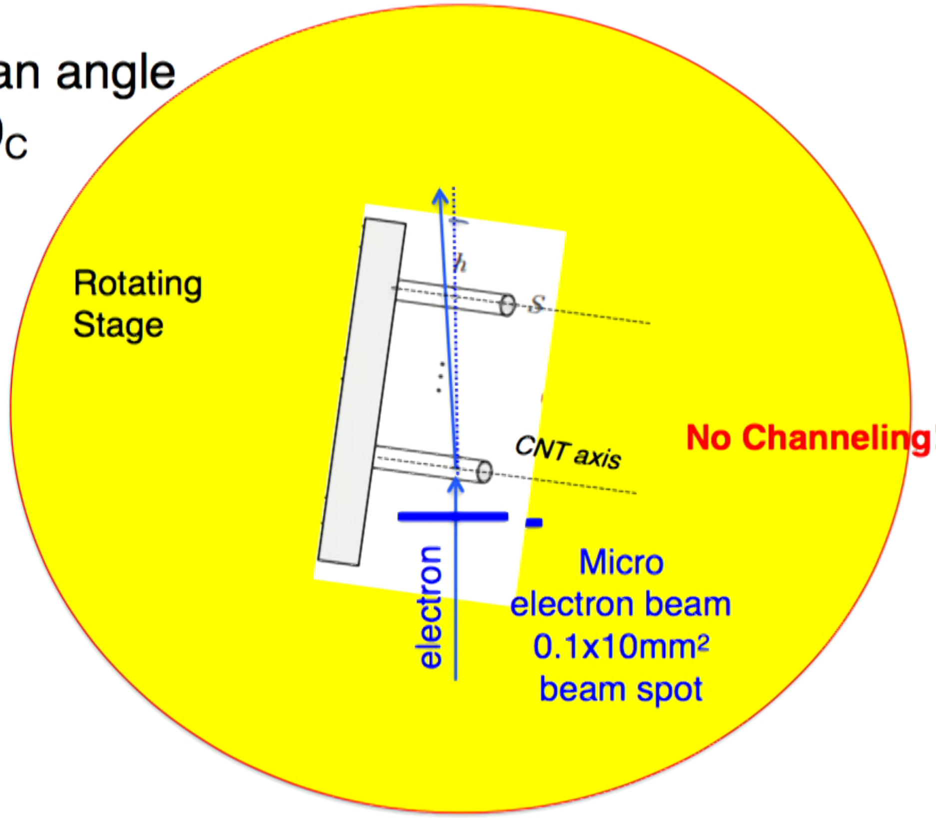
$$\tau_R = \frac{\pi(a^2 - \pi\rho^2)}{4 v_\perp (a - 2\rho)} = \text{time in shaded area}$$

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

[CIRILLO, CAVOTO, COCINA, FERRETTI, ADP EPJC (2016) 76]

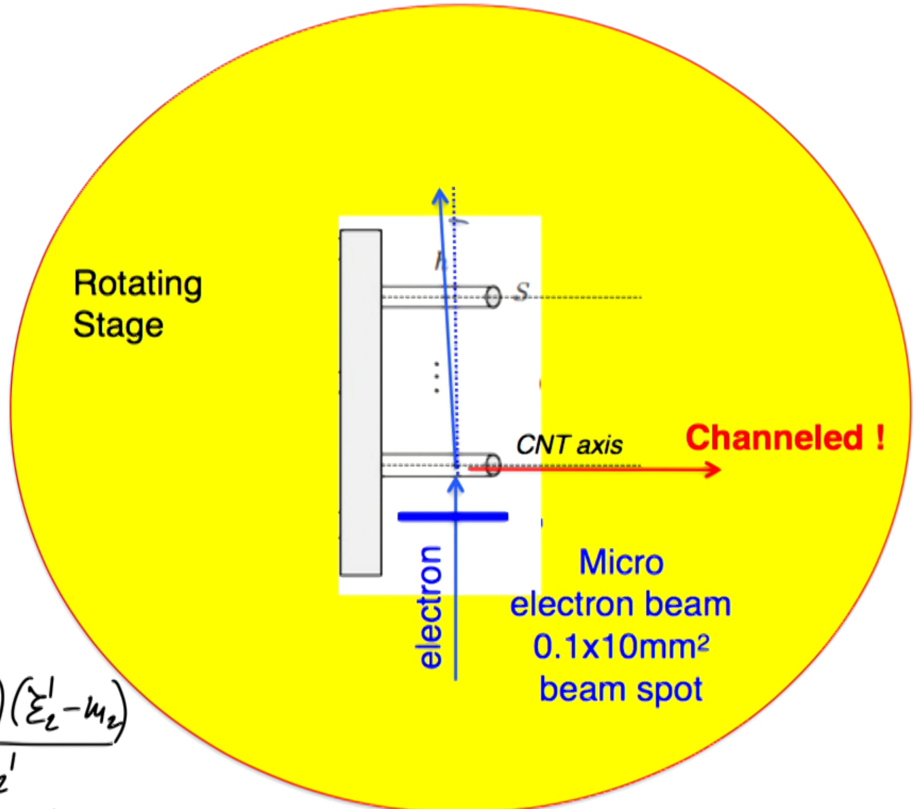
Experiment at BTF

Rotation by an angle wider than θ_C



Experiment at BTF:channeling

$\theta < \theta_C$



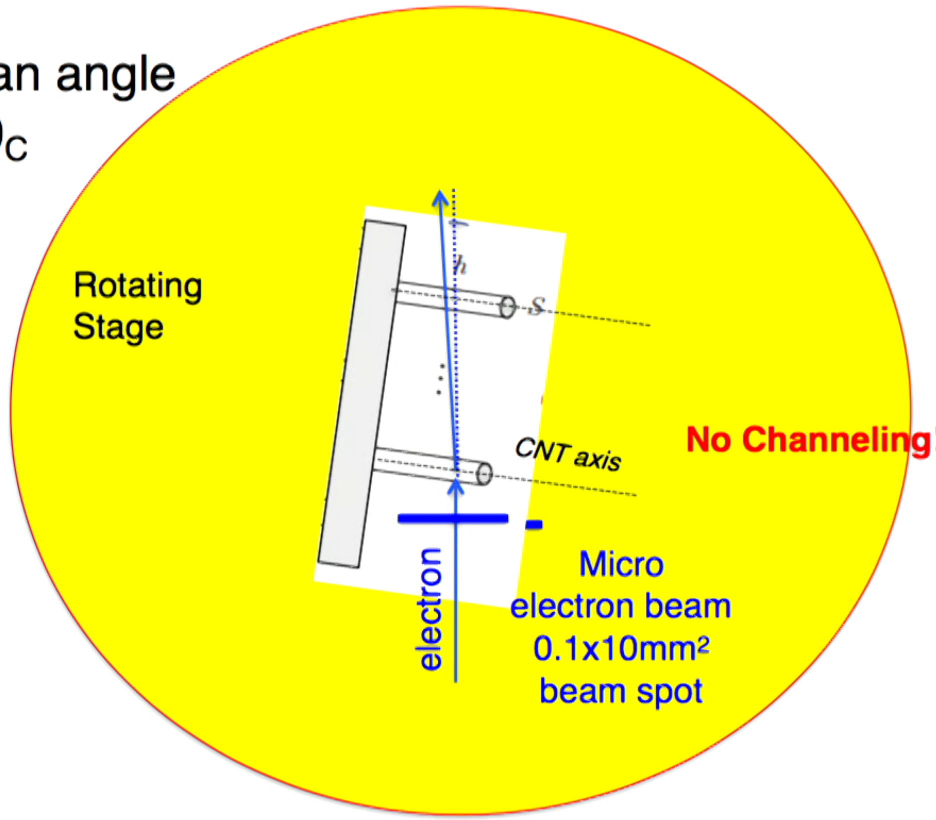
e^- at 500 MeV

$$\cos\theta_s = \frac{(E_1 + m_2)(E_2' - m_2)}{p_1 p_2'}$$

$E_1 \ll m_e \quad \theta_s \to \pi/2$

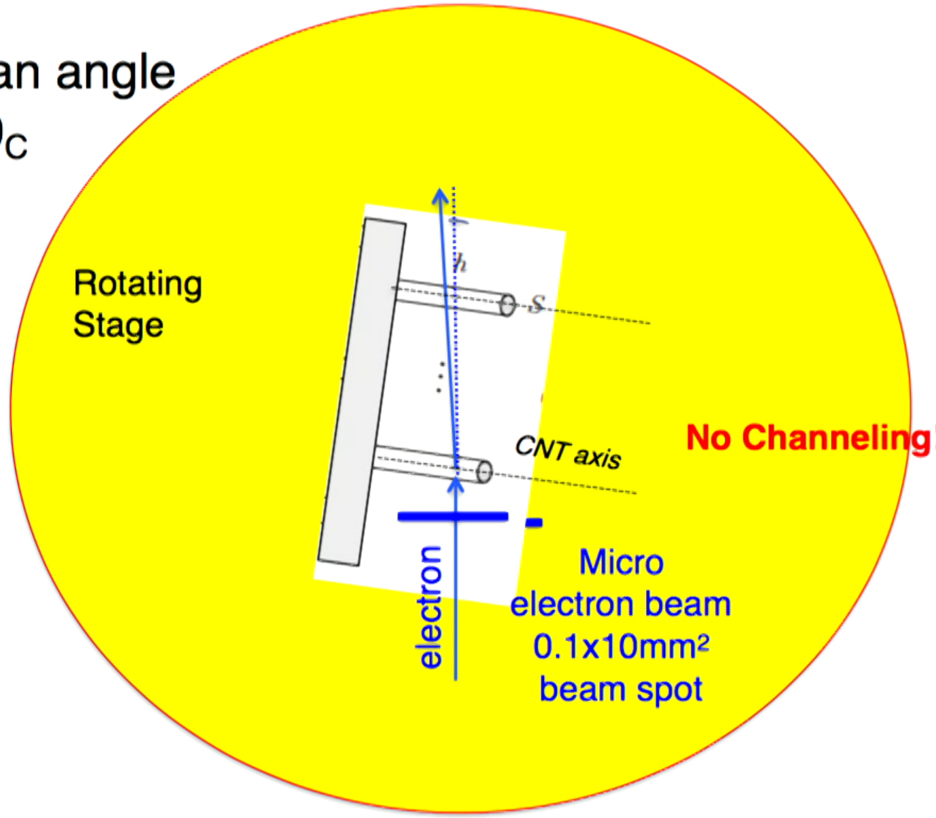
Experiment at BTF

Rotation by an angle wider than θ_C



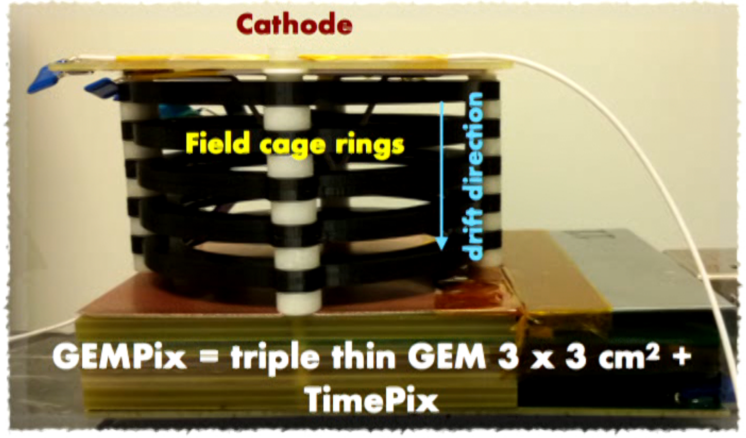
Experiment at BTF

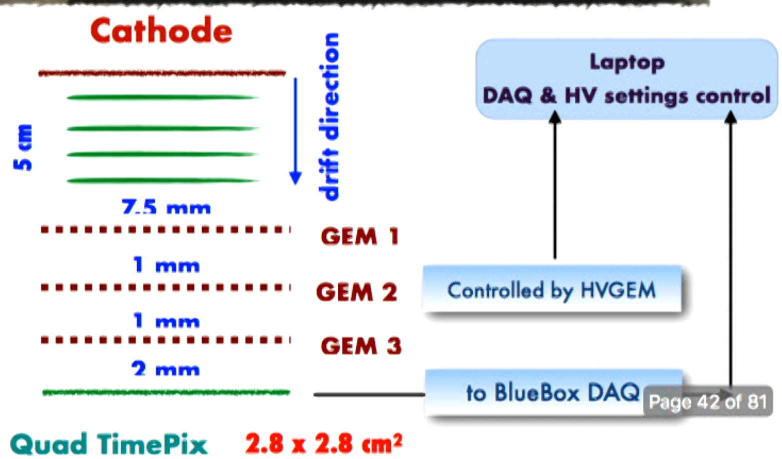
Rotation by an angle wider than θ_C



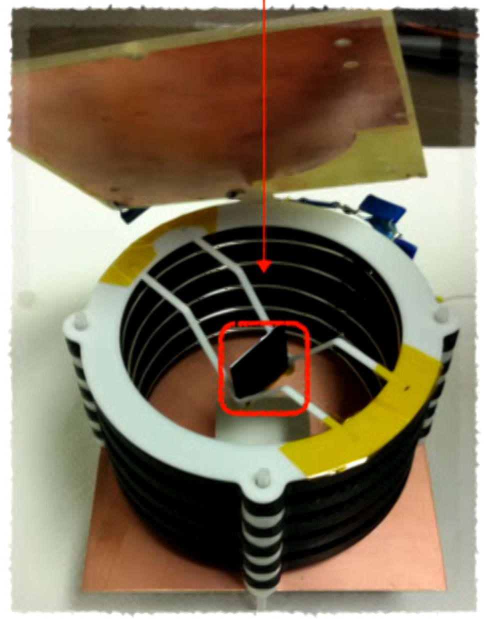
NITEC detector

INFN



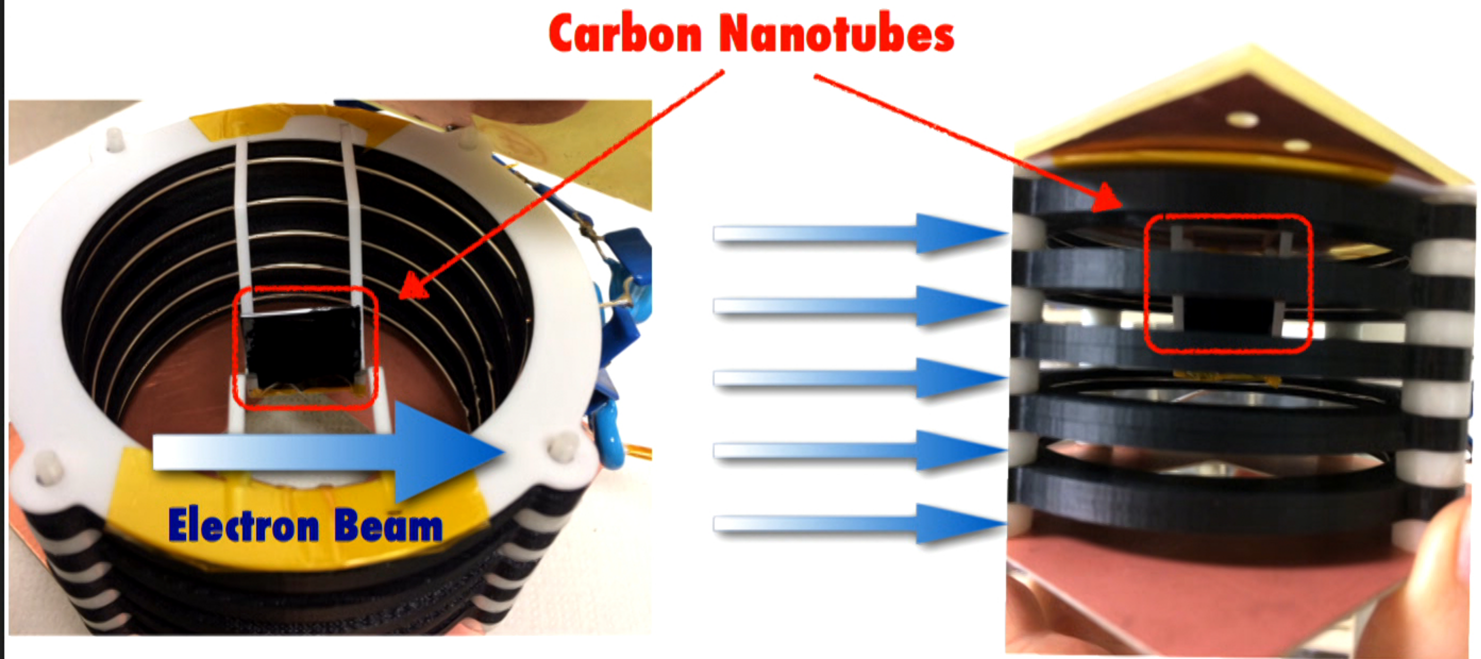


Carbon Nanotubes (see later)



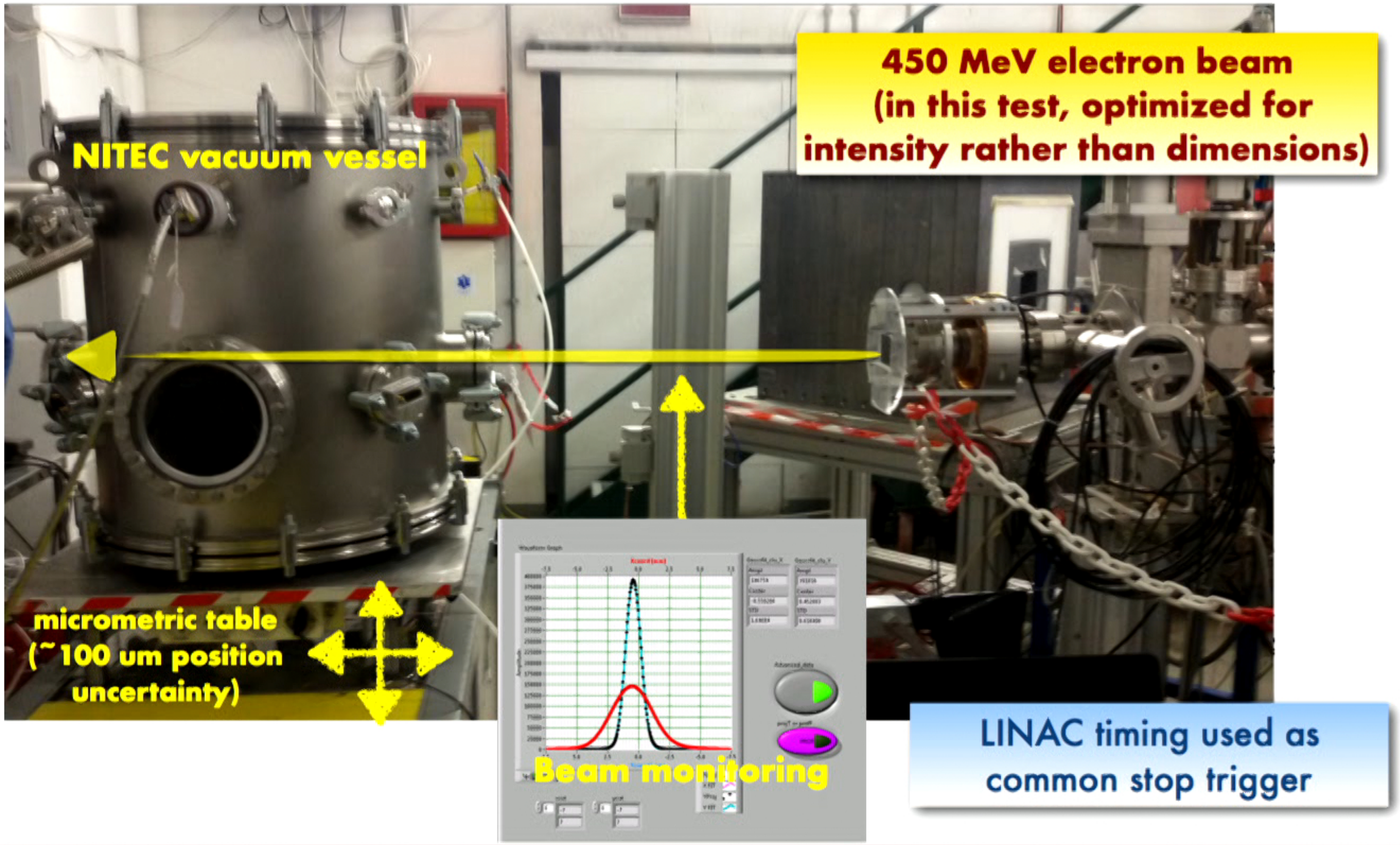
New field cage: rings support structure (in black in the picture) manufactured with 3D printer

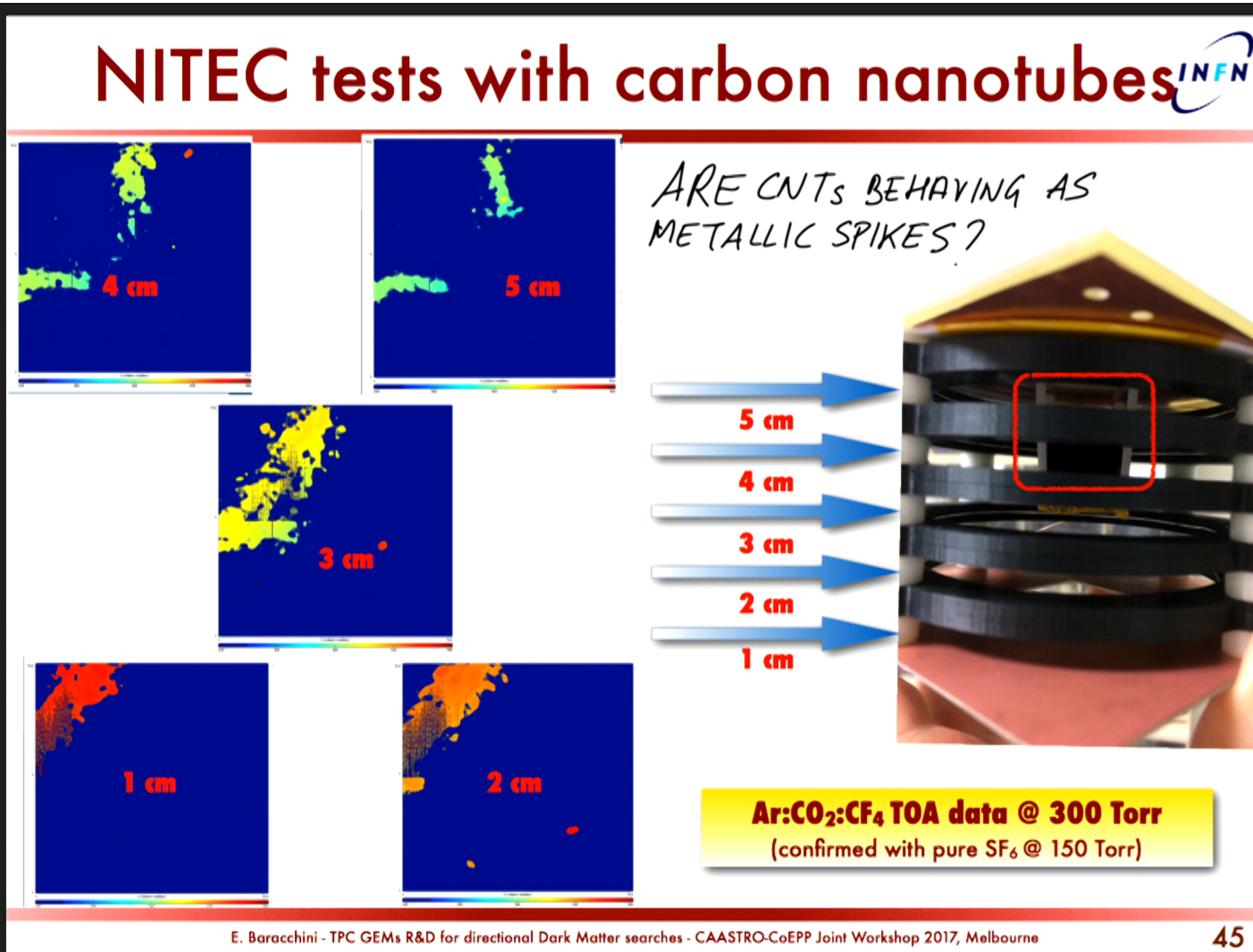
NITEC tests with carbon nanotubes



Beam on the side of nanotubes at various heights to study modification of the drift field

Measurement @ Beam Test Facility





NITEC tests with carbon nanotubes
INFN
ARE CNTs BEHAVING AS METALLIC SPIKES?
4 cm
5 cm
3 cm
1 cm
2 cm
5 cm
4 cm
3 cm
2 cm
1 cm
Ar:CO2:CF4 TOA data @ 300 Torr
(confirmed with pure SF6 @ 150 Torr)
E. Baracchini - TPC GEMs R&D for directional Dark Matter searches - CAASTRO-CoEPP Joint Workshop 2017, Melbourne
45

SIMP review

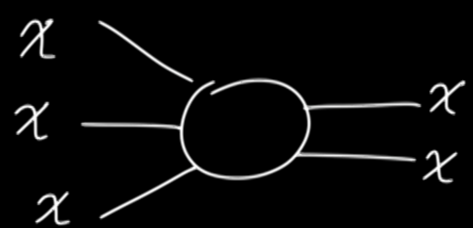
SIMPs

HOCHBERG, KUFLIK, VOLANSKY, WACKER PRL 113, 171301 (2014)

+ MURAYAMA PRL 115, 021301 (2015)

CARLSON, MACHACEK, HALL ASTROPHYS. J. 398 (1992) 43

DARK MATTER RELIC ABUNDANCE IS SET THERMALLY BY THE FREEZE OUT OF



THAT REDUCES THE # OF DM PARTICLES WITHIN THE DARK SECTOR. ANNIHILATIONS INTO SM PARTICLES ARE SUBDOMINANT AT FREEZEOUT

SIMPs

The $\phi(1020)$ is known to decay

$$\phi \to 3\pi$$
$$\phi \to K\bar{K} \qquad \text{(P-wave)}$$

Thus in principle we can have

$$K\bar{K} \to 3\pi$$

or

$$3\pi \to K\bar{K}$$

This is a strong decay with parity flip which can proceed (non-resonantly) through a term

$$\epsilon^{\mu\nu\rho\sigma}\, \mathrm{Tr}\left(\Pi\, \partial_\mu \Pi\, \partial_\nu \Pi\, \partial_\rho \Pi\, \partial_\sigma \Pi\right)$$

$$\Pi = \left(\textstyle\sum_a \xi^a \lambda^a\right) F_\pi \qquad (F_\pi \approx 93\,\mathrm{MeV})$$

SIMPs

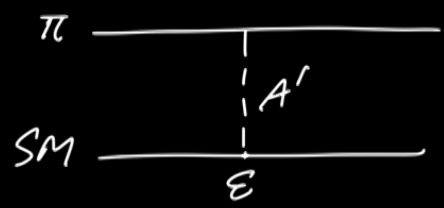
DM: PIONS OF A STRONGLY COUPLED QCD-LIKE HIDDEN SECTOR –

FROM REQUIRING THE VALIDITY OF χPT + CONSTRAINTS ON DM SELF INTERACTIONS

$$\boxed{150 < m_\pi < 800 \text{ MeV}}$$

The $3 \to 2$ process pumps heat into the DM gas. The rest mass of one of the π's is converted into KE. The energy density drops slower than for WIMPS.

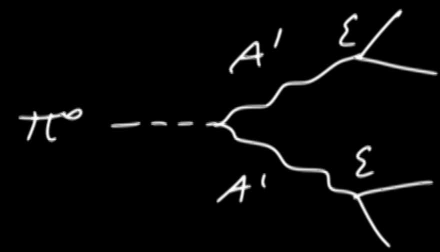
Find the way to dump this heat: ELASTIC SCATTERING ON SM.



The thermal contact between the two sectors can be obtained with dark photons as vector mediators.

SIMPs

— If ε is large enough then the π^0 in the dark sector could be unstable because of



$\propto \varepsilon^2 \, \mathrm{Tr}[Q^2 T^a]$

assume that $Q = \begin{pmatrix} \overbrace{+1 \;\; +1 \; \cdots}^{u} & \\ & \underbrace{-1 \;\; -1 \; \cdots}_{d} \end{pmatrix}$?

$\Gamma_\pi > H \longrightarrow$ deplete π and spoil DM abundance.

— Not enough to "kill" the anomaly.

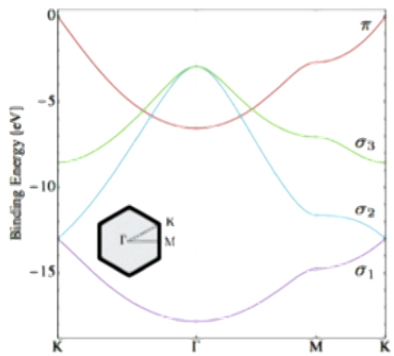
slower

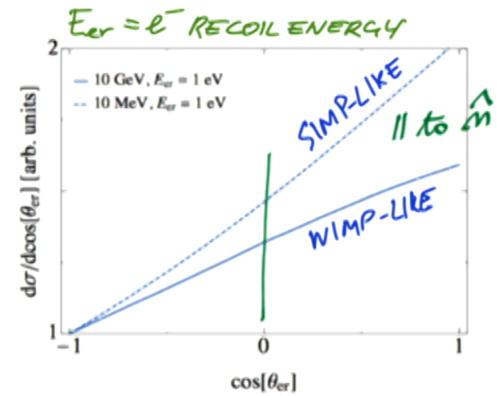
solution [Berlin et al: 1801.05805]

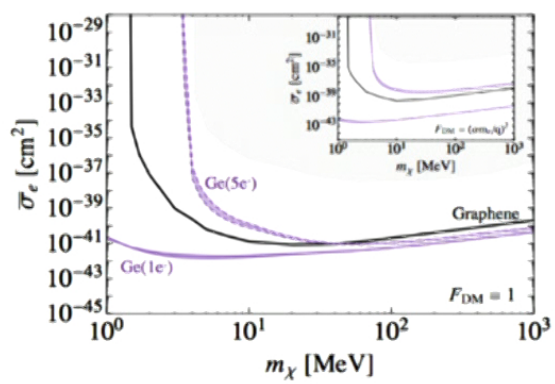
Electron recoils from graphene and cnts

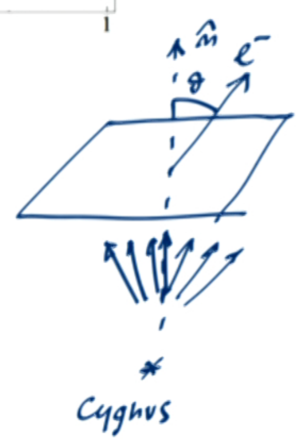
ELECTRON RECOILS FROM GRAPHENE SHEETS

HOCHBERG, KAHN, LISANTI, TULLY, ZUREK 1606.08849
using the PTOLEMY scheme.









02/04/2017

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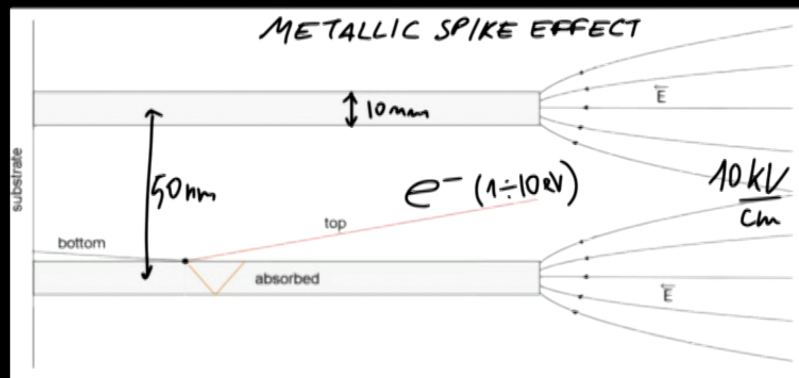
DM-Weizmann

Electrons from CNTs



$$E' = \frac{R^2}{r^2} E$$

$$I(\mu A) = 7.5\ \frac{E'[V/nm]}{\phi^{3/2}[eV]} \exp\left(-6.8\ \frac{\phi^{3/2}}{E'}\right) \coth\left(5.6\ \frac{\phi^{1/2}}{2E'r}\right)$$

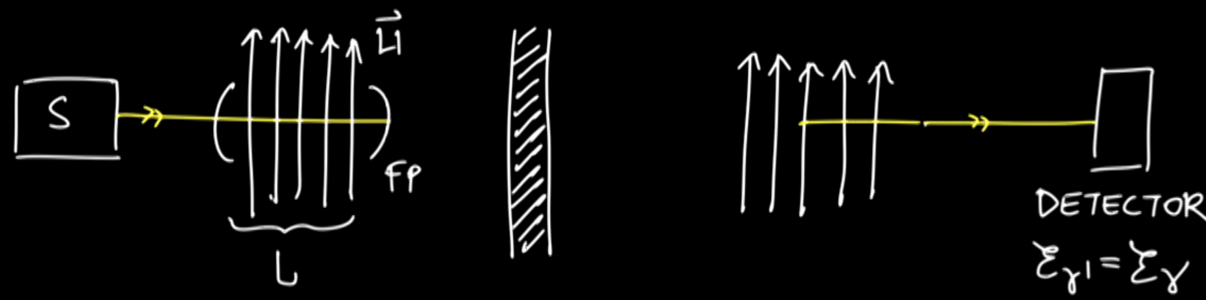
Fowler-Nordheim Theory of field emission by metallic CNTs.

$I \approx \exp(10^{-3})$ being $\phi = 4eV$ (cfr. 20eV for a C atom)

[CAVOTO, LUCHETTA, ADP PLB 776 (2018) 338]

Axion-like particles with sub-THz light

Light shining through wall



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

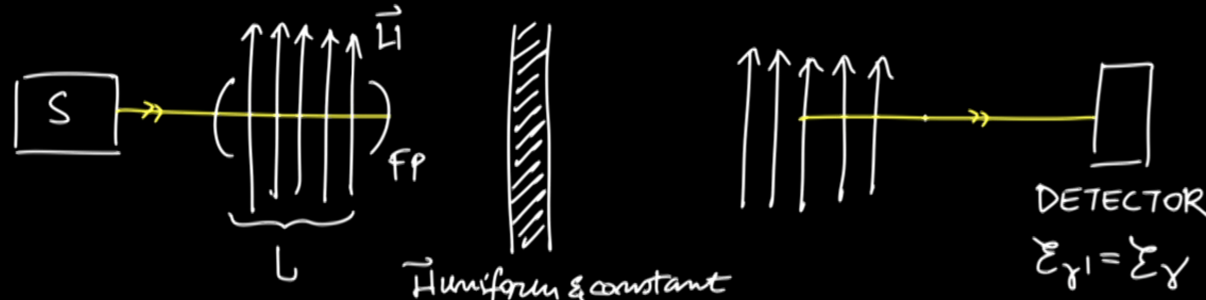
$$\propto \dot{N}_\gamma \, (G H L)^4$$

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

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

for $H = 15\,\mathrm{T}$ along $15\,\mathrm{cm}$.

Light shining through wall



$$\dot{N}_{evts} \propto \dot{N}_\gamma \, (G H L)^4$$

1 MEGAWATT GYROTRON SOURCES CAN YIELD

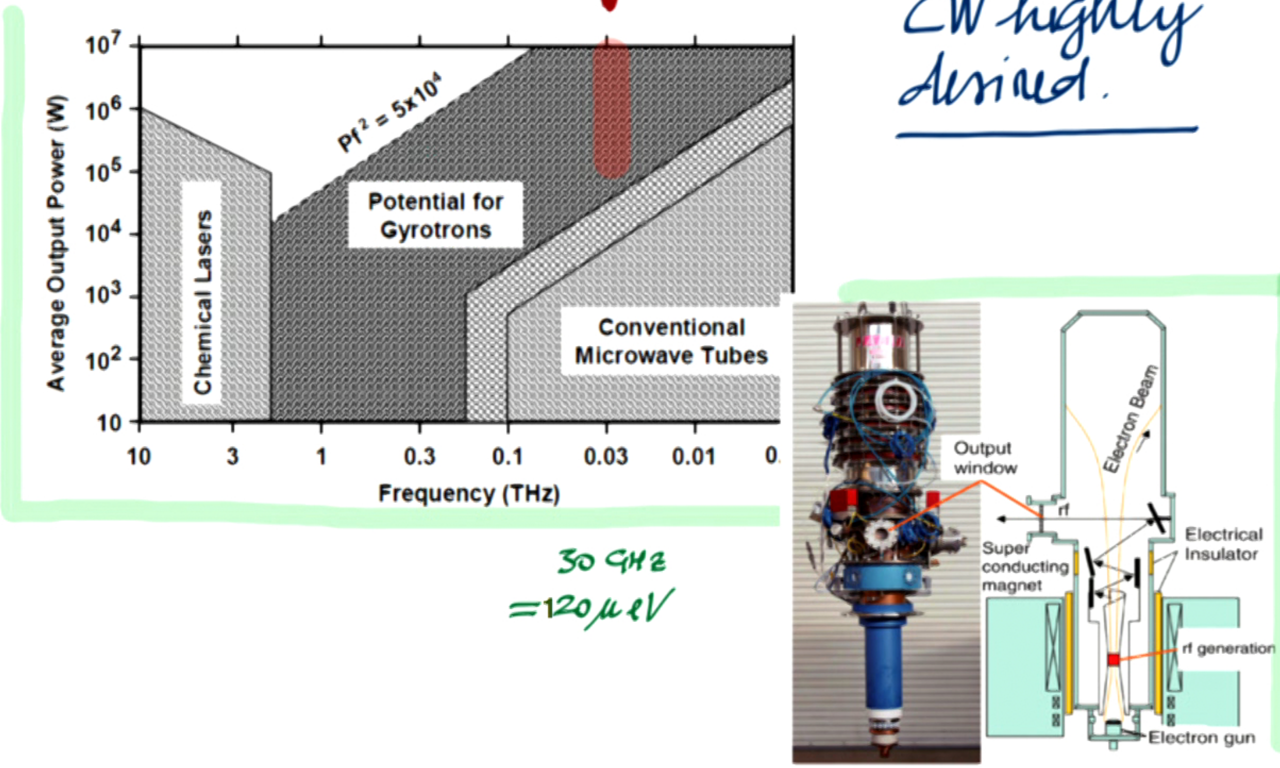
$$\dot{N}_\gamma \sim 10^{28} \; \gamma/sec \quad @ \, 30 GHz \; (1 cm)$$

WITH CONTINUOUS EMISSION (over 10 orders of magnitude more photons wrt standard visible laser sources)

$\rightarrow$ 10 L.S.W. $\frac{evts}{\gamma}$ $\times$ Q of the cavity $(10 \div 10^4)$

Gyrotrons

CW highly desired.



30 GHz
=120 μeV

23/09/15

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laxotalk

Potential Reach

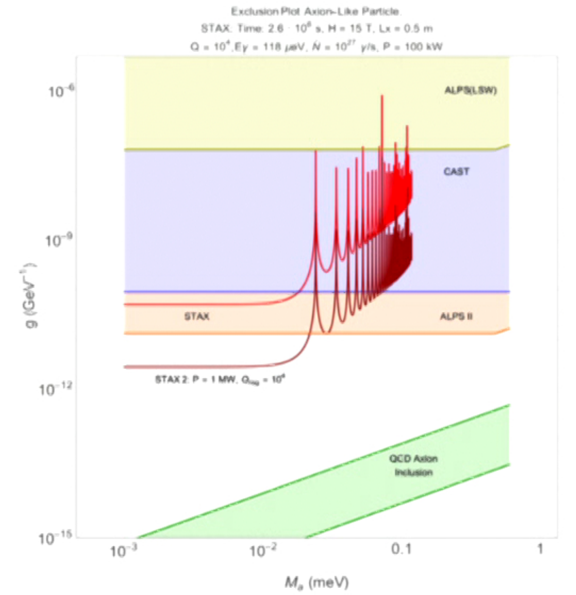

Fig. 3. 90% CL exclusion limits that STAX may achieve in case of a null result for axions with $m_a \lesssim 0.02$ meV. An exposure time of one month and zero dark counts are considered. 'STAX' and 'STAX 2' configurations correspond to a 100 kW and 1 MW gyrotron sources respectively. The former provides 10^{27} γ/s at 30 GHz.

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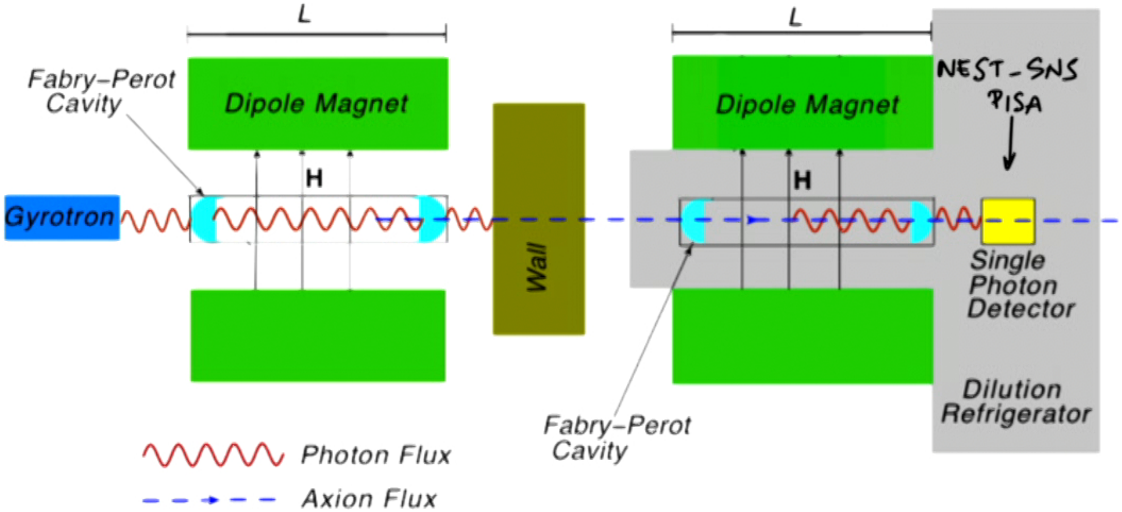
[CAPPARELLI, CAVOTO, FERRETTI, GIAZOTTO, ADP, SPAGNOLO
Phys Dark Uni 12 (2016) 37]

STAX scheme

CERN AGREED TO GIVE TWO SPARE QUADRUPOLES FOR THIS EXPERIMENT.



10 mK

100 KW STAX I ($\dot{N}_\gamma = 10^{27}\ \gamma/s$)

1 MW STAX II

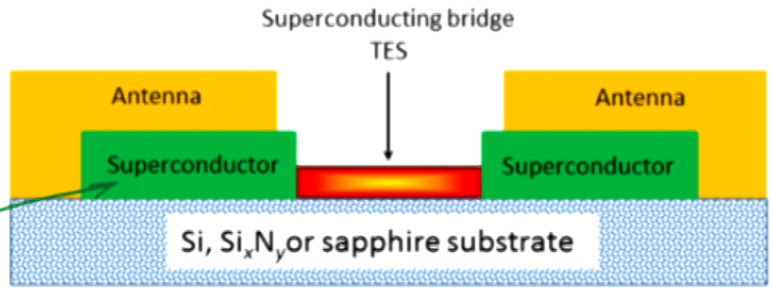
$$P = (GH)^4 L^2 L^2 \rightarrow (GH)^4 Q L^2 L^2$$

explore values of G smaller by $Q^{-1/4}$

30 GHz γ-DETECTION

1. SINGLE-γ detection ← CRYOGENIC (10 mK)
2. MW screening
3. ...

⋮



- $T_c < 20\,\mathrm{mK}$
- α-W, Ti-Au, Ti-Cu
- $V \sim 10^{-3} \div 10^{-4}\,\mu m^3$
- low noise SQUID readout.

21/02/16

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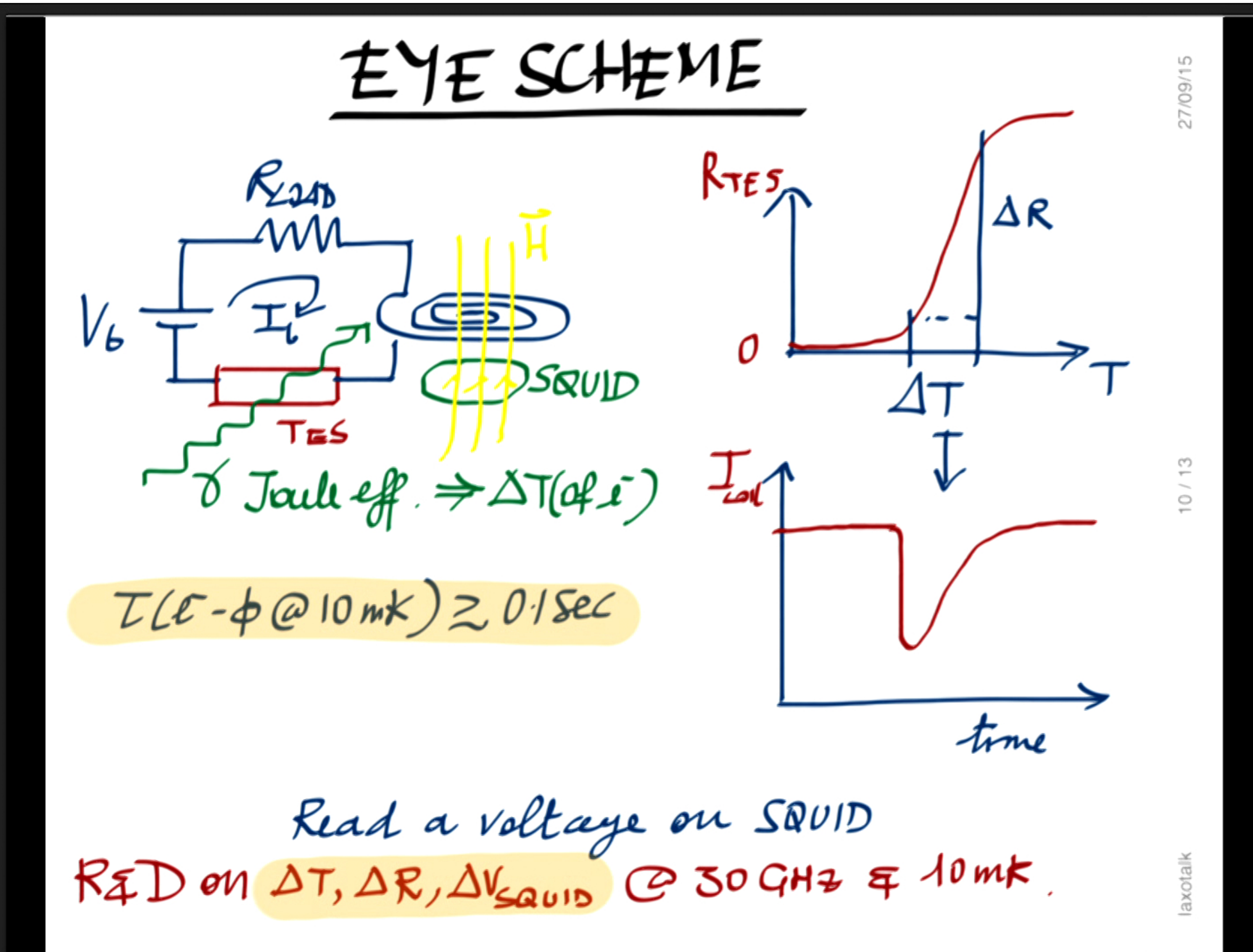
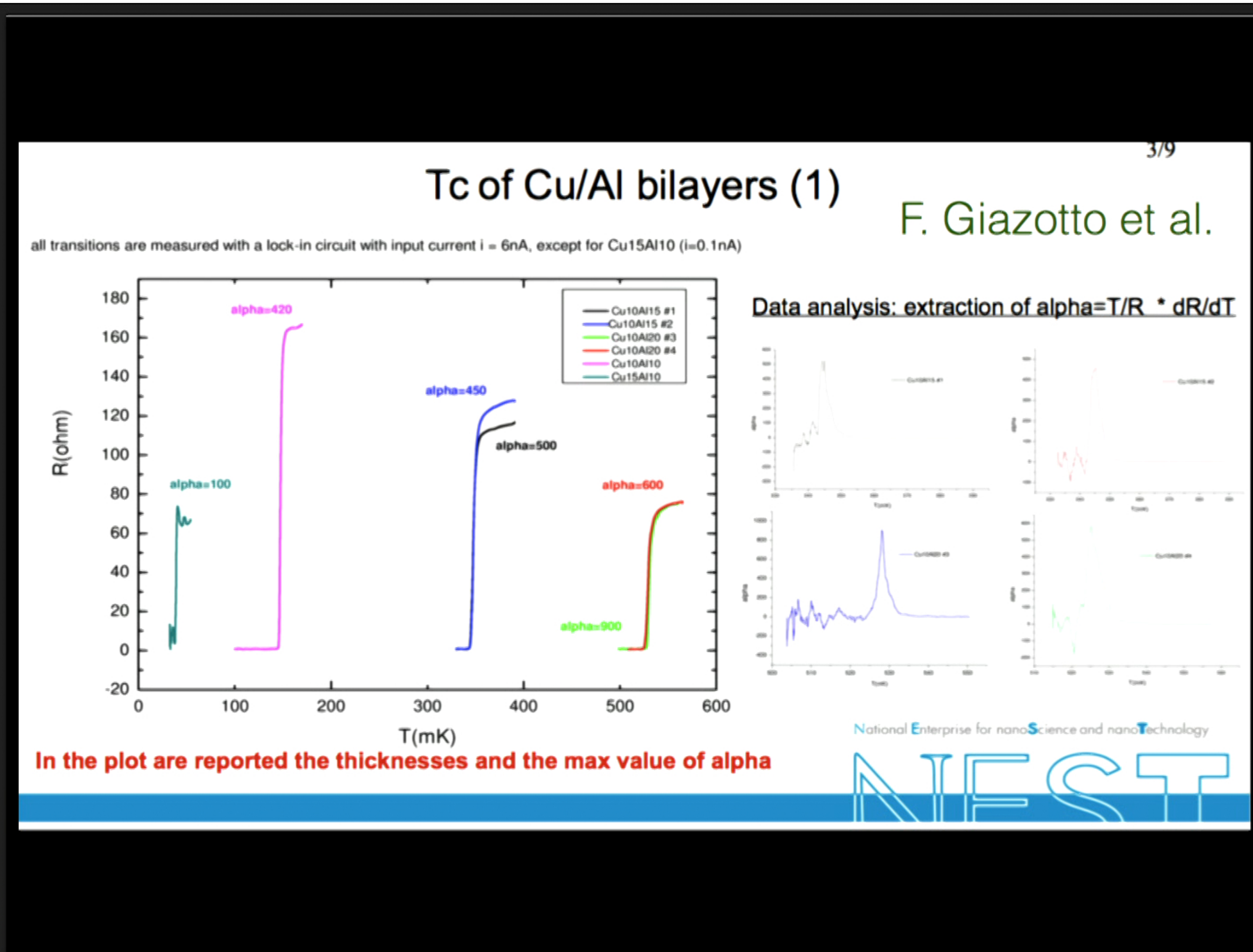
Axions2


EYE SCHEME
R LOAD
V b
I b
H
SQUID
TES
γ Joule eff. ⇒ ΔT(of e⁻)
τ(e-φ @ 10 mK) ≳ 0.1 sec
R TES
0
ΔR
T
ΔT
I coil
time
Read a voltage on SQUID
R&D on ΔT, ΔR, ΔV SQUID @ 30 GHz & 10 mK.
27/09/15
10 / 13
laxotalk



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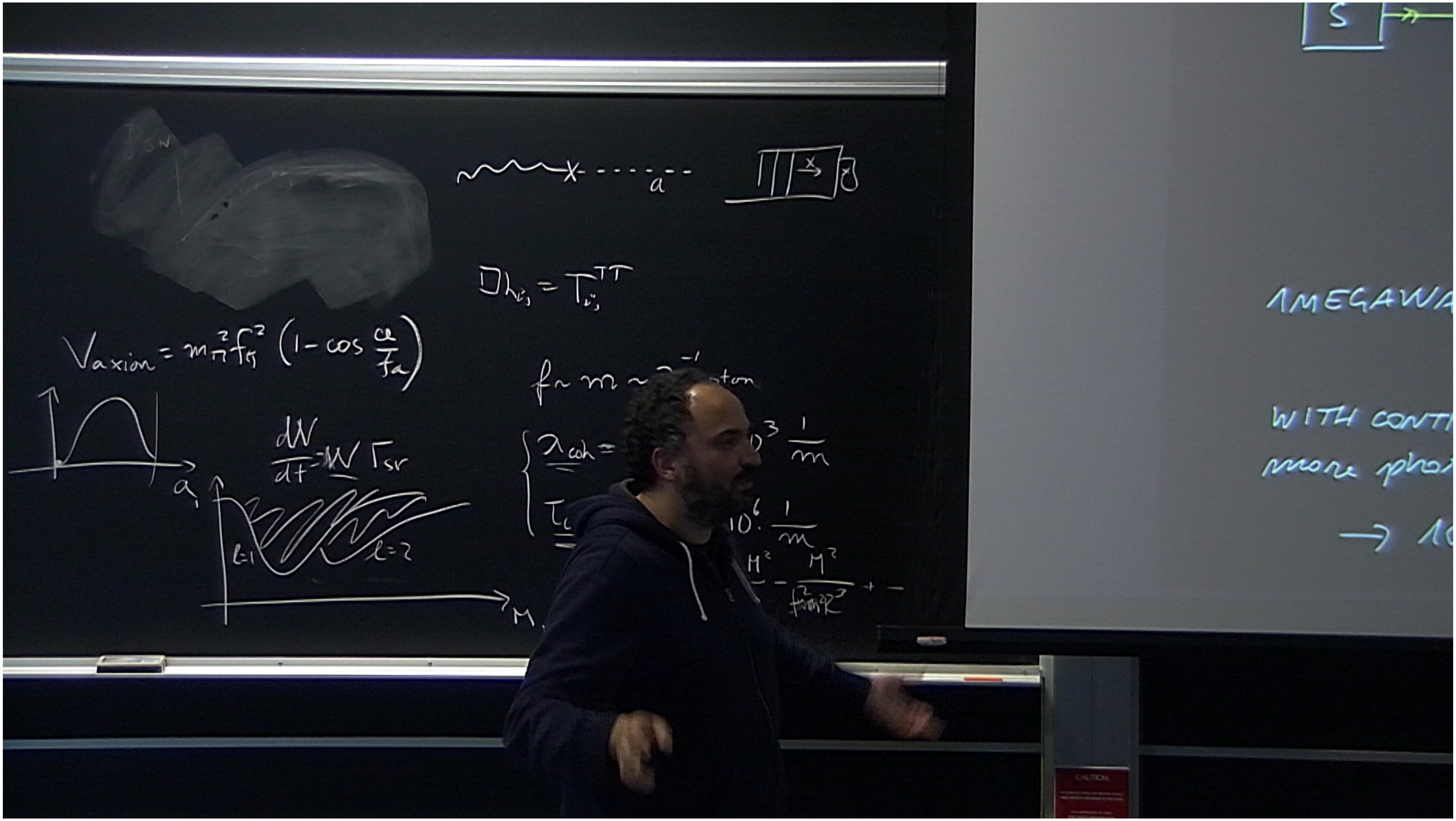
Tc of Cu/Al bilayers (1)
F. Giazotto et al.
all transitions are measured with a lock-in circuit with input current i = 6nA, except for Cu15Al10 (i=0.1nA)
Data analysis: extraction of alpha=T/R * dR/dT
alpha=420
alpha=450
alpha=500
alpha=100
alpha=600
alpha=900
Cu10Al15 #1
Cu10Al15 #2
Cu10Al20 #3
Cu10Al20 #4
Cu10Al10
Cu15Al10
R(ohm)
T(mK)
In the plot are reported the thicknesses and the max value of alpha
National Enterprise for nanoScience and nanoTechnology
NEST

Concluding remarks

- 2d targets for light Dark Matter could be a good way to supersede existing methods — the Ptolemy experiment proposal (C. Tully) and its DM search version, is seriously being considered to access GS Labs.
- Light Dark Matter might be searched with semiconductors, superconductors and superfluid targets (see papers by Hochbrg, Zurek et al.)
- Ideas to exploit molecular vibrations and more.



$V_{axion} = m_\pi^2 f_\pi^2 \left(1 - \cos \frac{a}{f_a}\right)$
$\frac{dN}{dt} = N\,\Gamma_{sr}$
$\Box h_{ij} = T_{ij}^{TT}$
AMEGAWA
WITH CONT
more pho