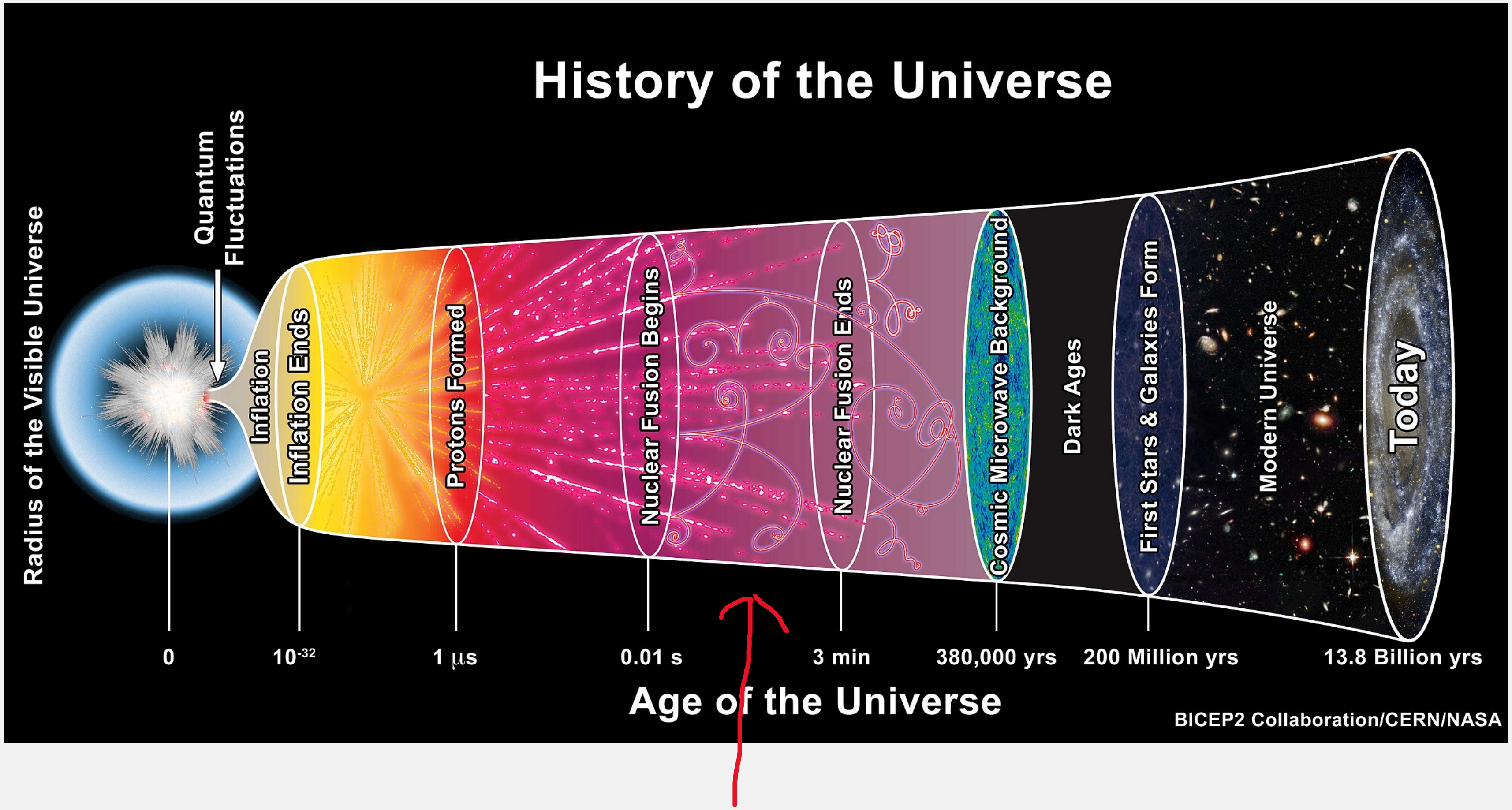
Detecting relic neutrinos with tritium on graphene: the PTOLEMY project

Nicolo de Groot (Radboud University and Nikhef)

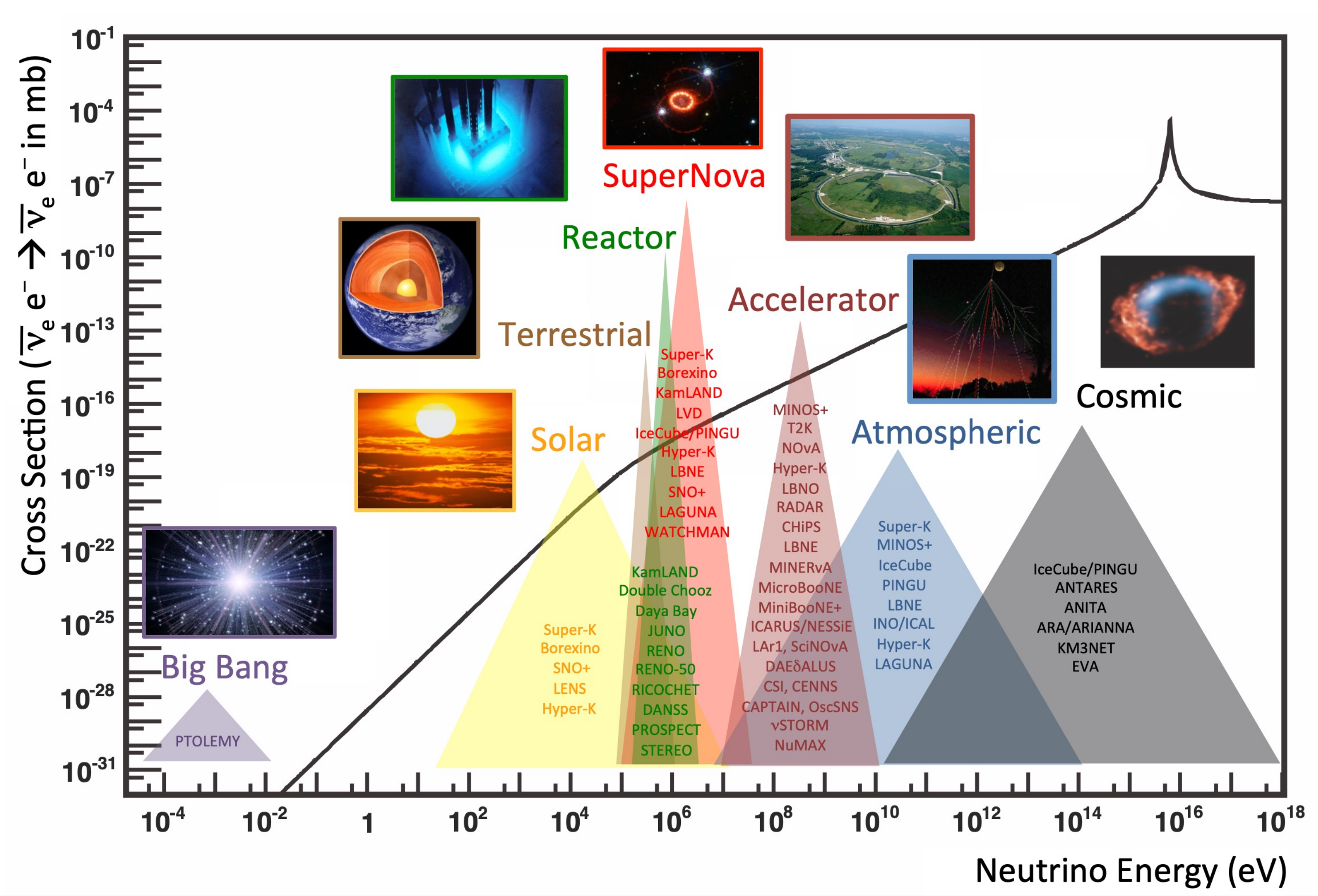
for the PTOLEMY collaboration



~1 s: neutrinos decouple

Ptolemy

Neutrinos sources across the Cosmos



Relic Neutrino Background

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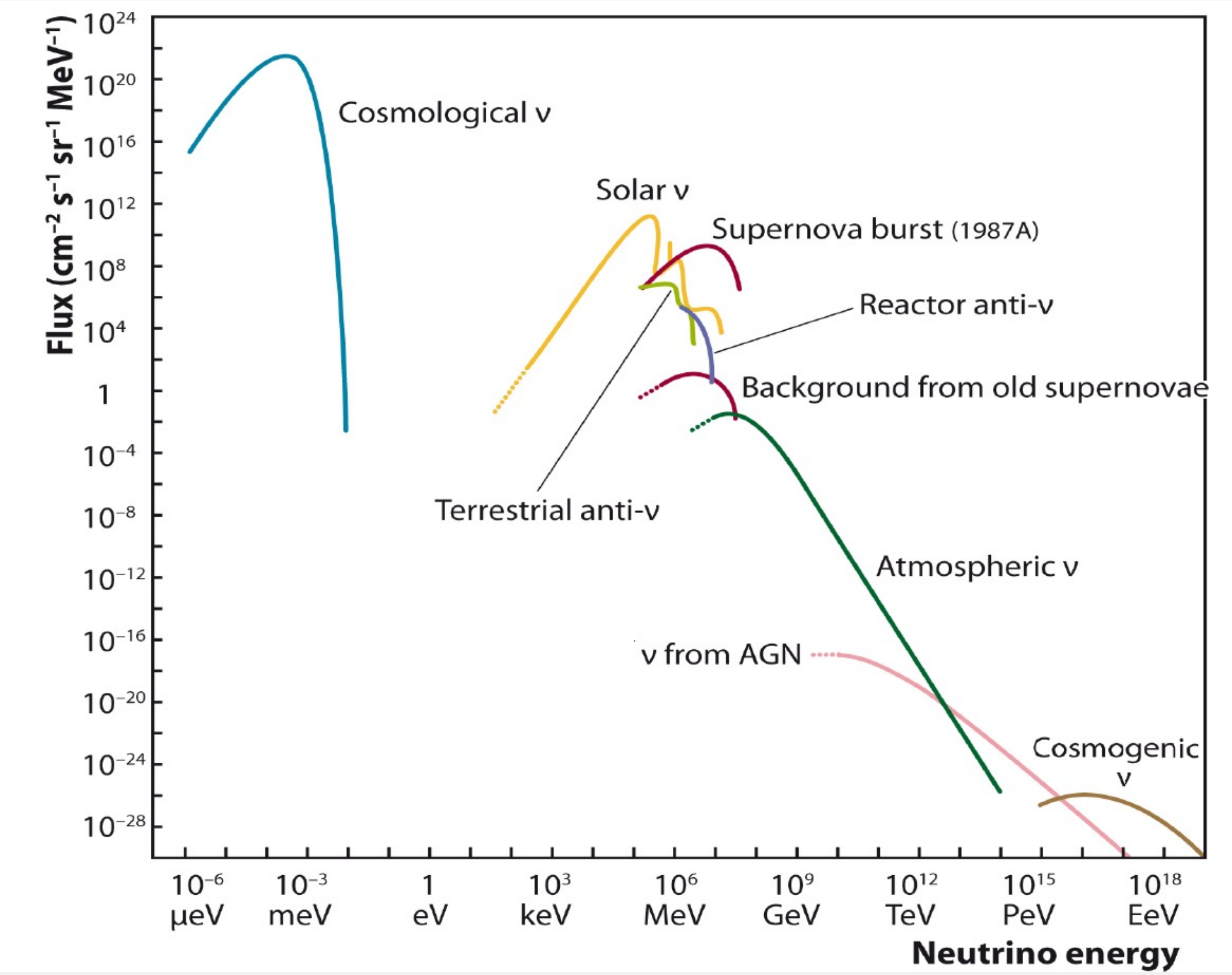
Number density:

$n_\nu = 112/\mathrm{cm}^3$

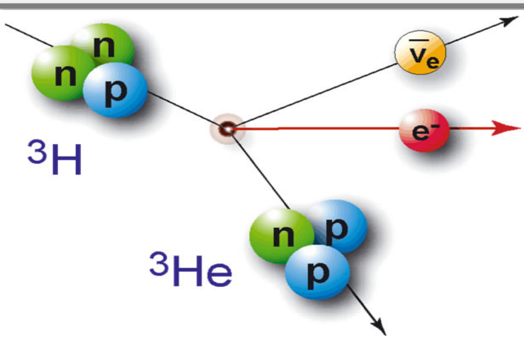
Temperature:

$T_\nu \sim 1.95\mathrm{K}$

(p ~ 0.17 meV)

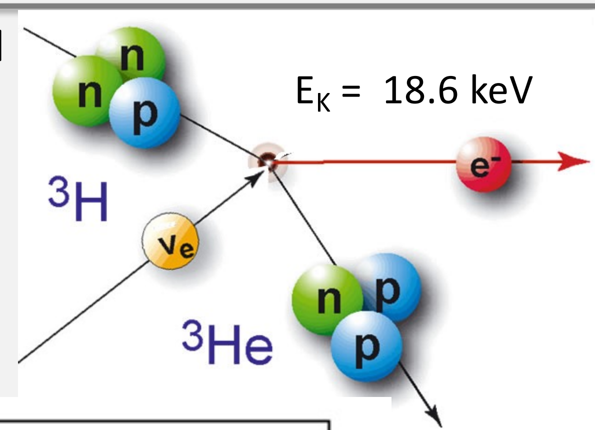


Relic Neutrino Capture



S. Weinberg [*Phys. Rev.* 128:3, 1457 (1962)]
A.G.Cocco, G.Mangano and M.Messina.
[JCAP 06(2007)015 DOI: 10.1088/1475-7516/2007/06/015]

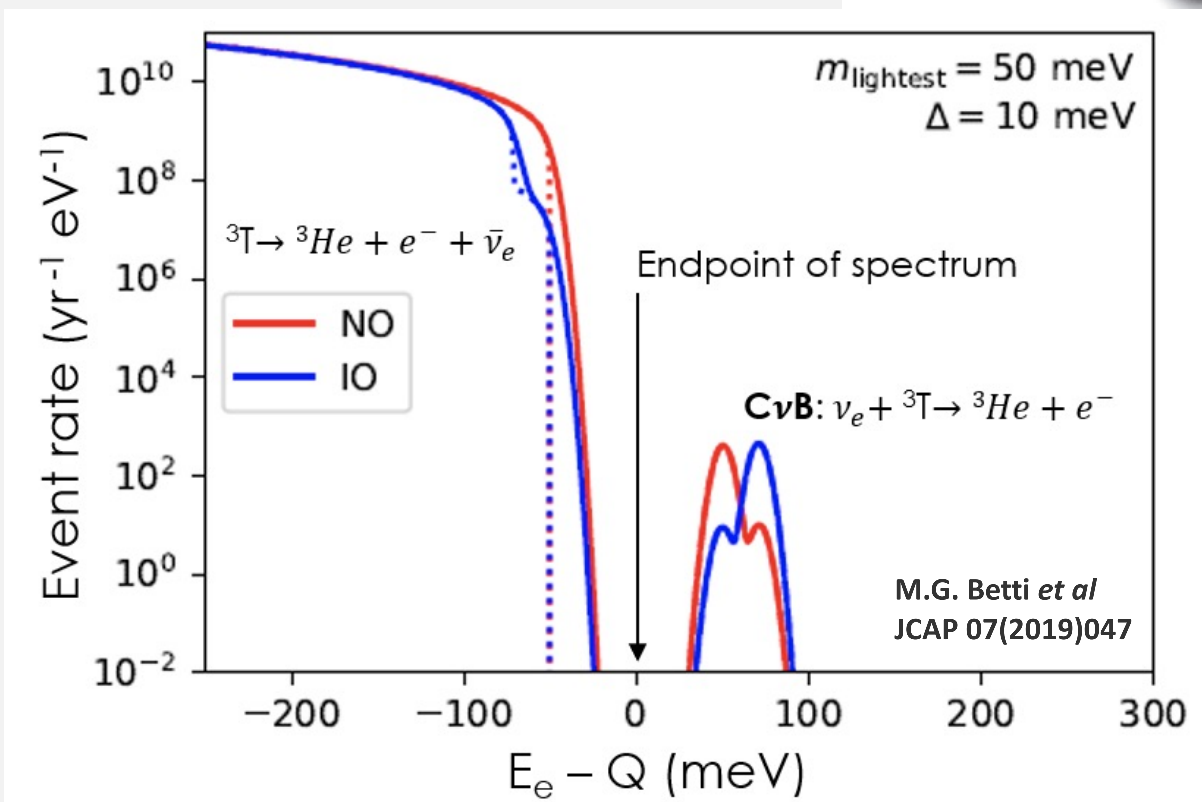
Tritium β-decay
(12.3 yr half-life)



Gap (2m) constrained to
m ≲ 200meV
from **precision cosmology**

Neutrino flavor expected
with **m ≳50meV**
from **oscillations**

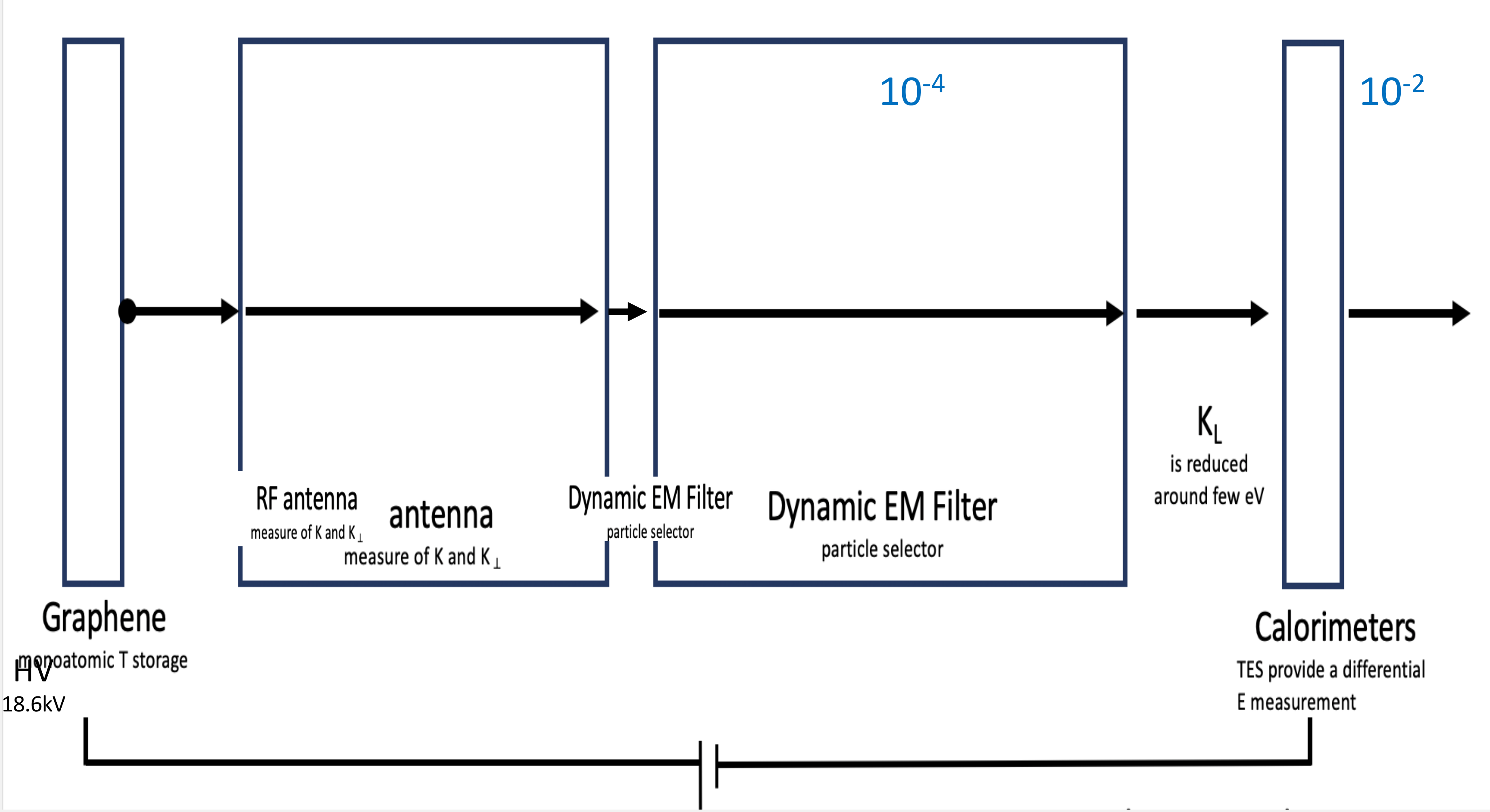
Ptolemy aim: <50meV
100g of T



PTOLEMY World-Wide Collaboration

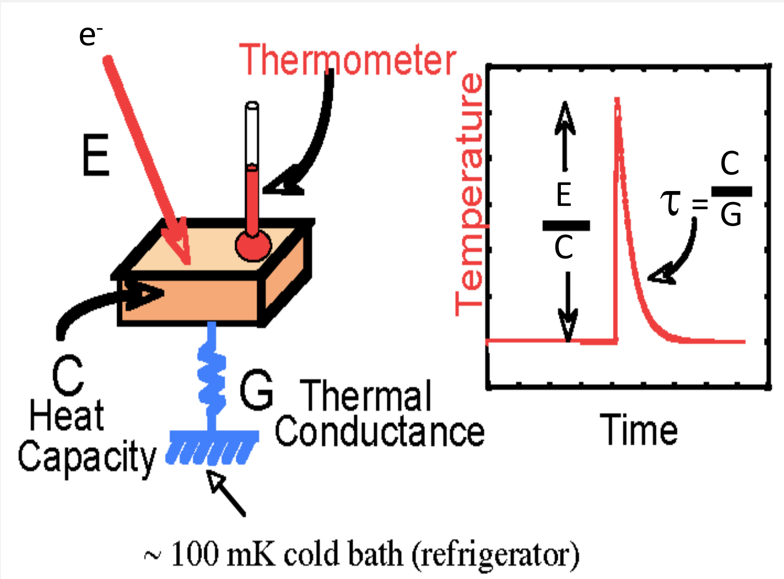
More than 40 physicists and 22 I institutions

PTOLEMY Basic concept



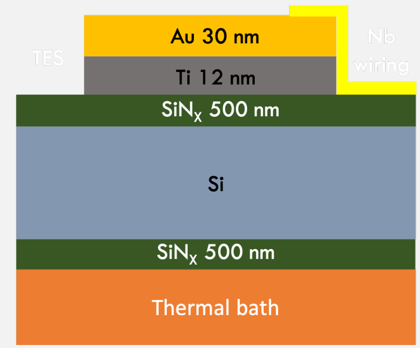
$$E_{Total} = q\left(V_{TES} - V_{Target}\right) + E_{RFcorr} + E_{cal}$$

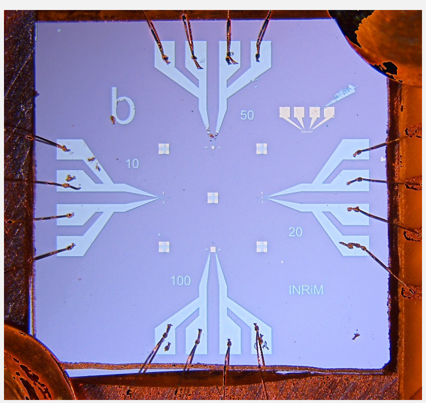
Calorimeter: TES µCal

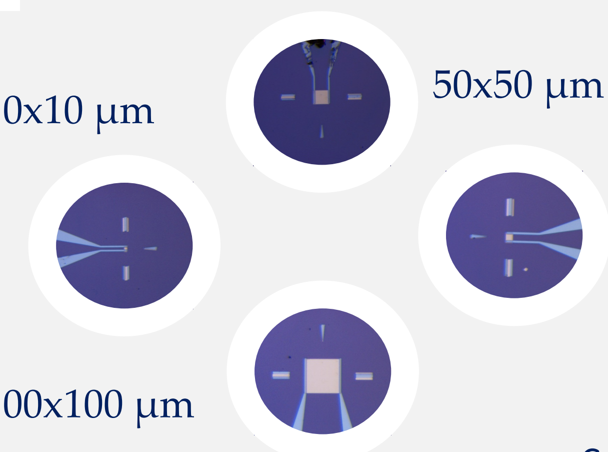


Thin sensors:

~1 eV electron can be stopped with very small C







10x10 µm

50x50 µm

20x20 µm

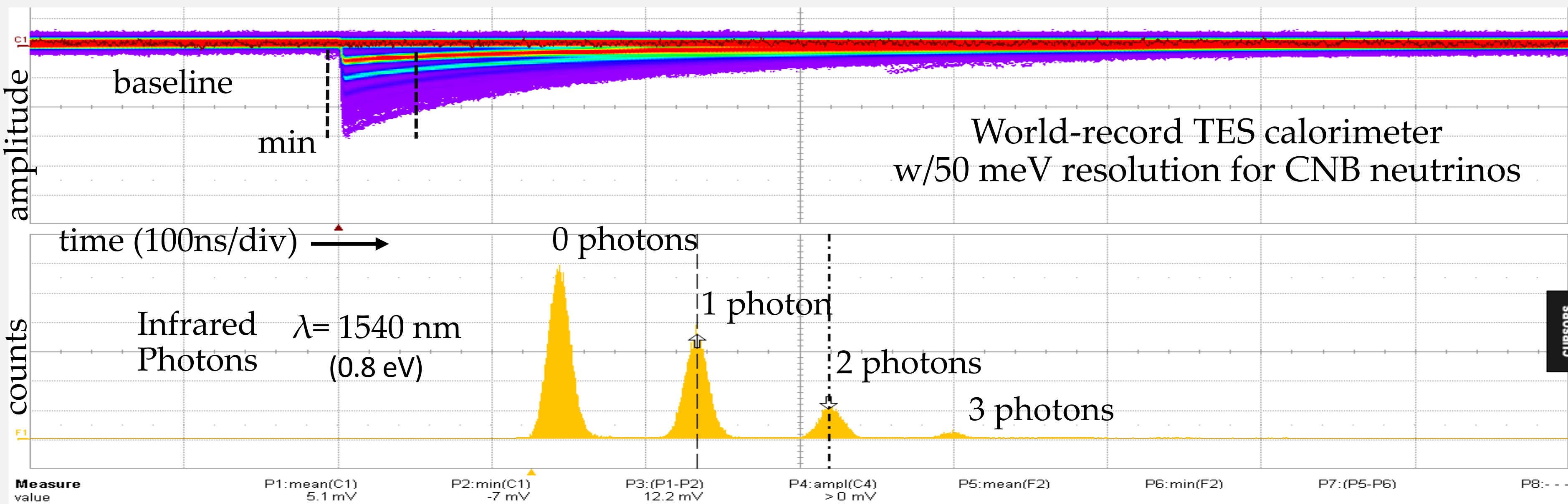
100x100 µm

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

C. Pepe, E. Monticone, M. Rajteri

Mauro Rajteri, Eugenio Monticone and others, https://doi.org/10.1007/s10909-019-02271-x
"TES Microcalorimeter for PTOLEMY", J. Low Temp. Phys. 199 (2020) 138-142.

1% energy resolution at optical photon energies, i.e. measures the wavelength of a 500nm photon to a few nm



C. Pepe, E. Monticone, M. Rajteri

Ptolemy filter concept

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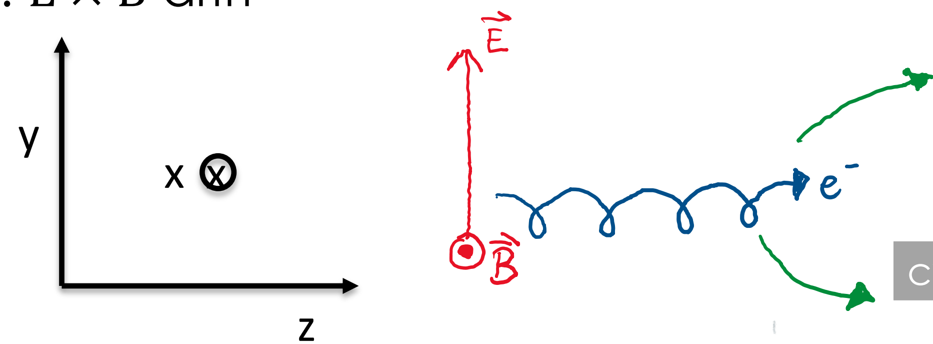
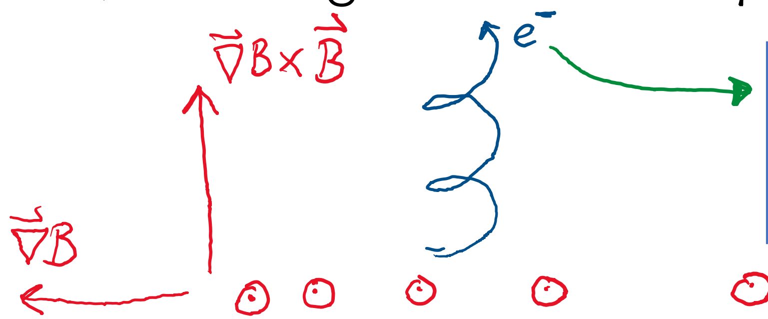
I: $\vec{E} \times \vec{B}$ drift



1. net drift, $v_{drift} = E/B$
2. no work, drift along equipotential planes

cyclotron motion – detectable RF

II: $\frac{\mu}{B^2}\vec{\nabla}B \times \vec{B}$ drift, with magnetic moment $\mu = \frac{m_e v_\perp^2}{2B}$



1. net drift, $v_{drift} = \mu \frac{|\vec{\nabla} B|}{B}$
2. Allows E field to work (!): $\frac{dT_\perp}{dt} = e\vec{E} \cdot \vec{v}_{drift}$

$\vec{B}$

$$V^y_{E\times B}(z)|_{x,y=0} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B_x^2} = \frac{E_z B_x \hat{\boldsymbol{y}}}{B_x^2} = \frac{E_z}{B_x}\hat{\boldsymbol{y}}$$

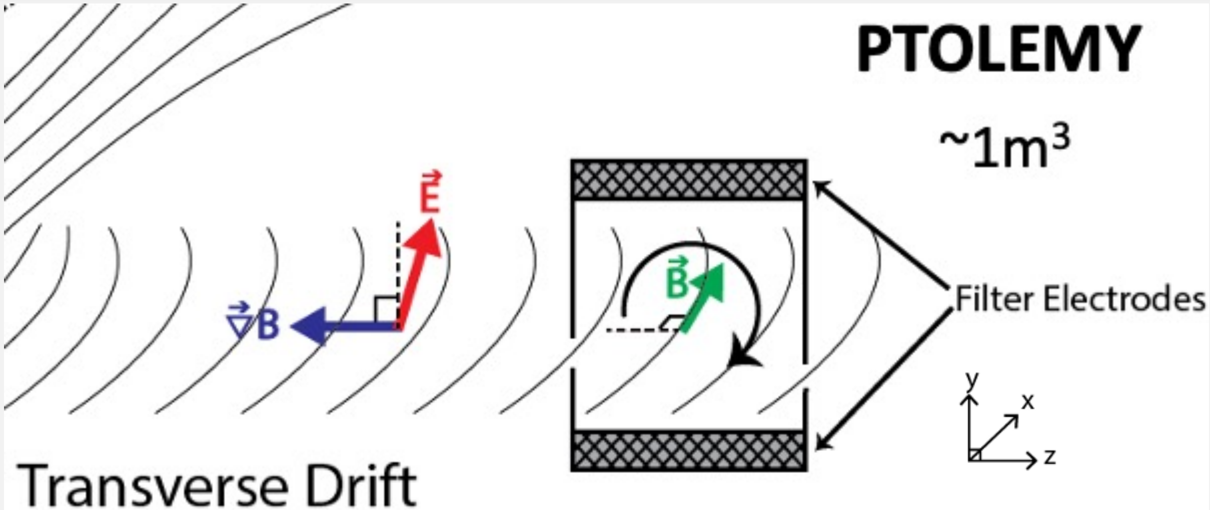
$$V_{\nabla B}(z)|_{x,y=0} = -\frac{\boldsymbol{\mu} \times \boldsymbol{\nabla}_\perp \boldsymbol{B}(z)}{qB(z)} = -\frac{\mu}{qB_x}\frac{dB_x}{dz}\hat{\boldsymbol{y}}$$

Enforce zero drift in y (rotate E)

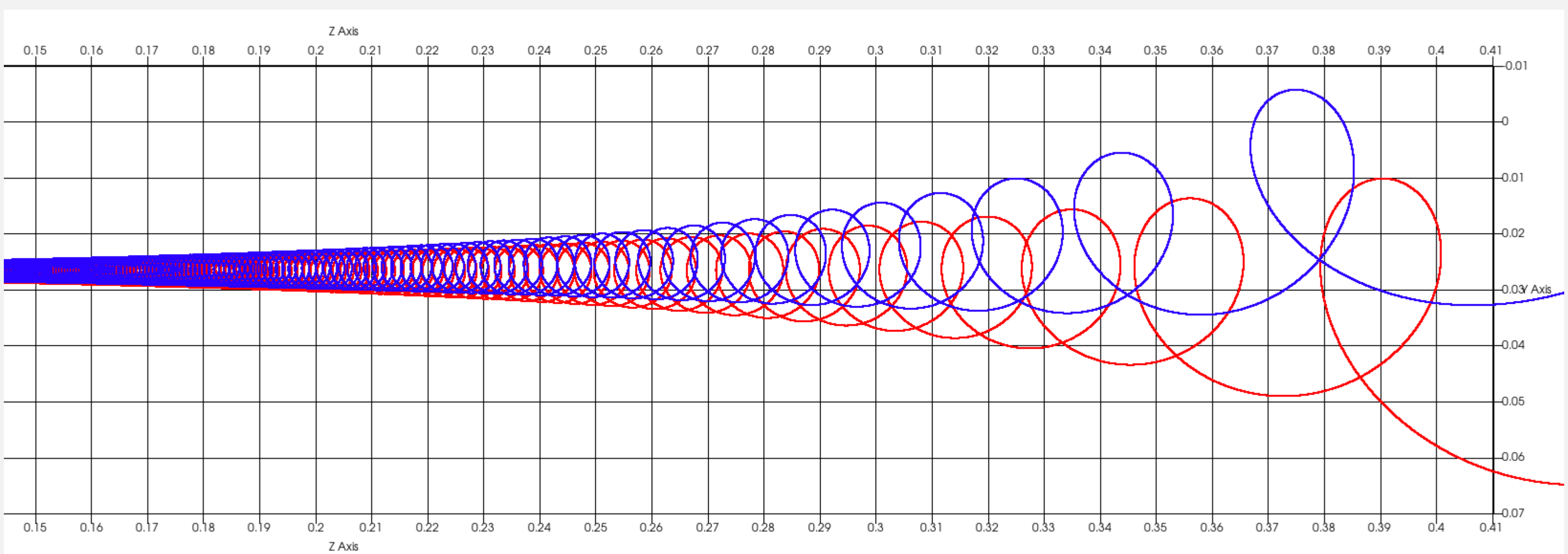
$$\xrightarrow{\text{yields}} \quad E_z(z)|_{y=0} = -\frac{\mu}{q}\frac{dB_x(z)}{dz}$$

A.P Colijn, (PATRAS2019)

Ptolemy filter



Simulations with KASSIOPEIA code (KATRIN) and Lorentz4 (N. Rossi, M. Messina, LNGS)
https://github.com/gkrossi/lorentz4

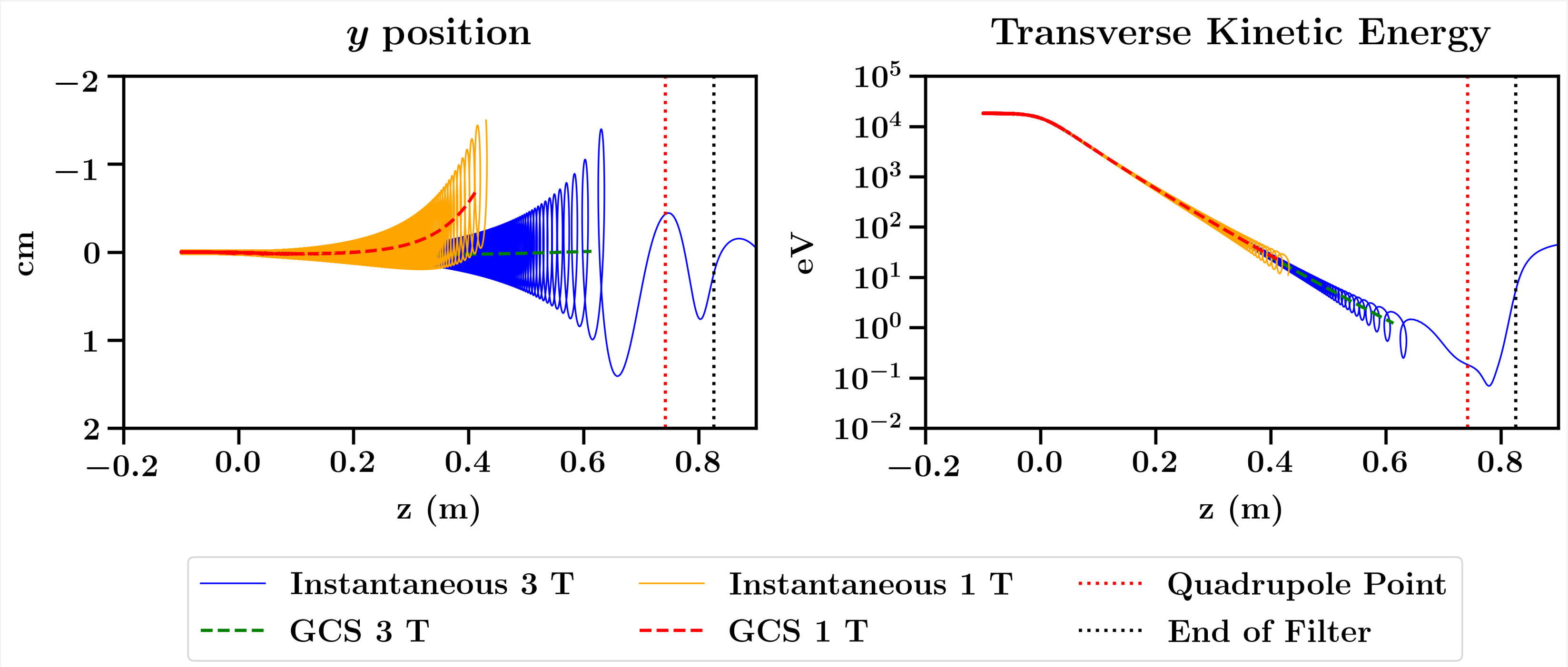


Filter Performance

Improves as B^2 for a fixed filter dimension

18.6 keV @ 1T → ~10eV (in 0.4m)

18.6 keV @ 3T → ~1eV (in 0.6m)



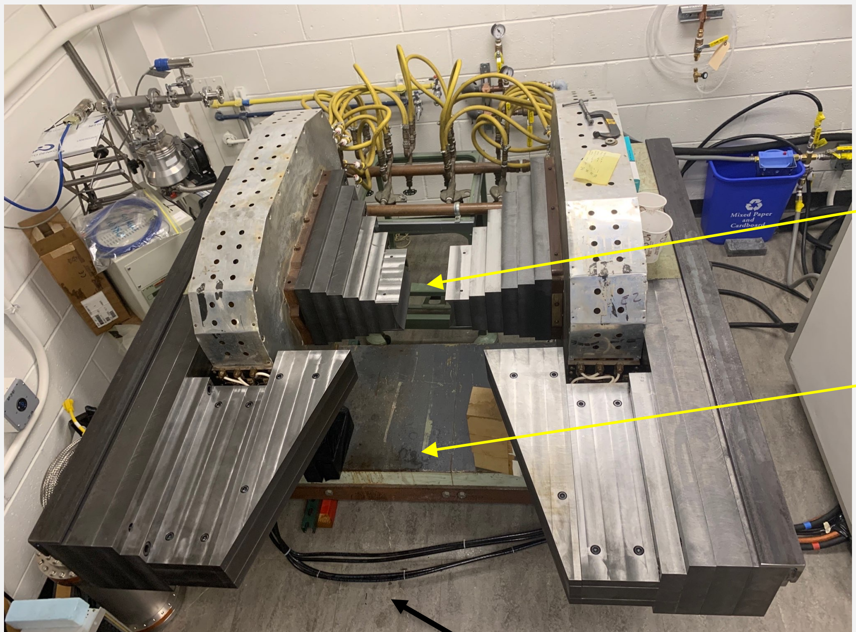
PTOLEMY Collaboration, https://arxiv.org/abs/2108.10388
"Implementation and Optimization of the PTOLEMY Electromagnetic Filter"

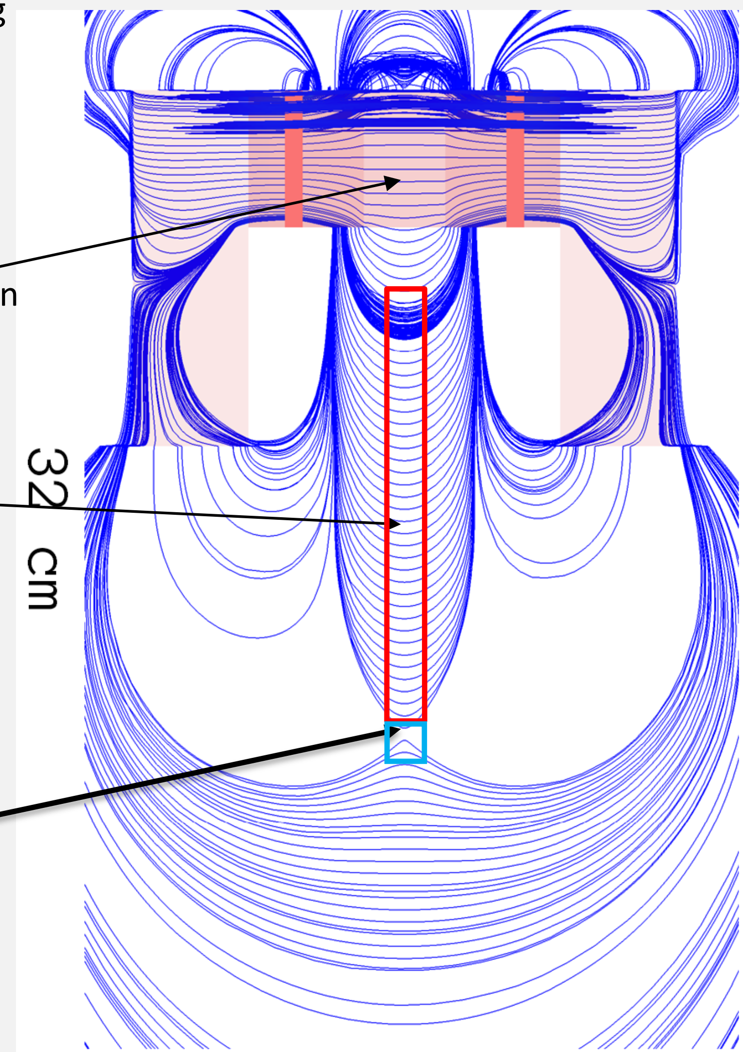
https://iopscience.iop.org/article/10.1088/1748-0221/17/05/P05021

First Version of the PTOLEMY filter

PTOLEMY
filter@Princeton

Wonyong Chung





RF pickup region

Filter region

Andi
Tan

Zero field (location for TES microcalorimeter)

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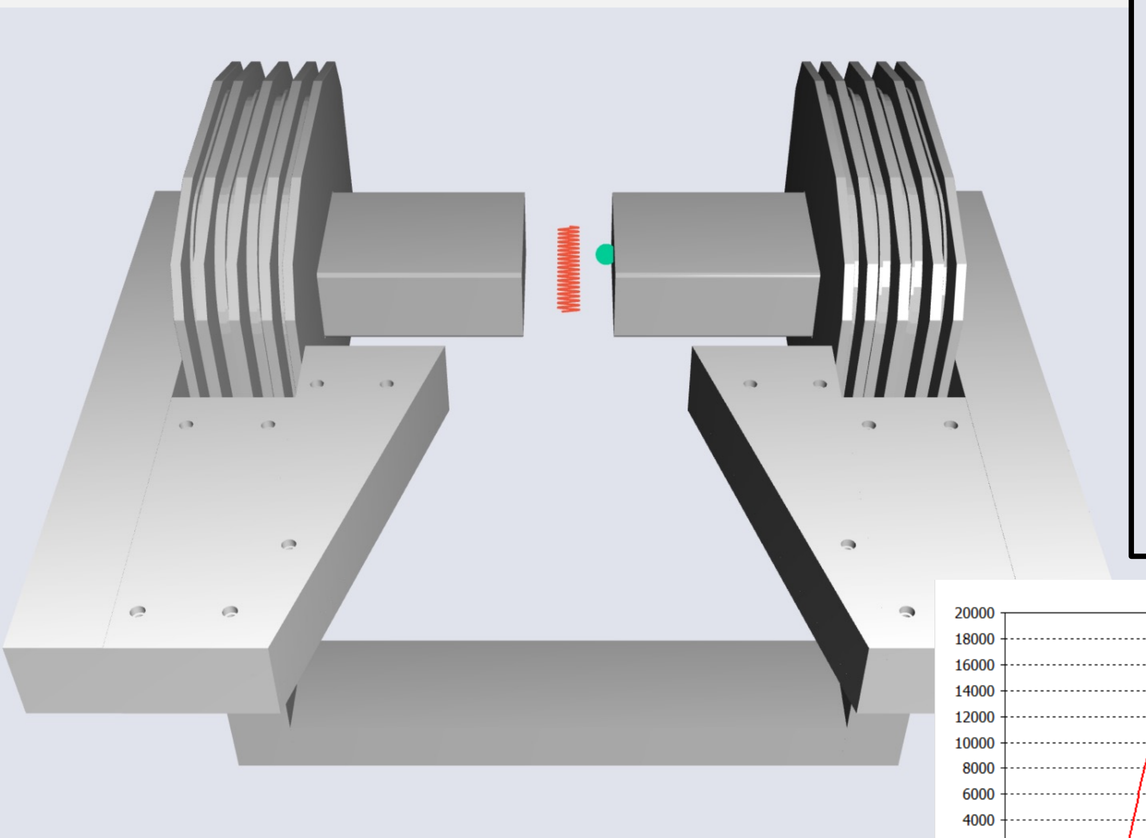
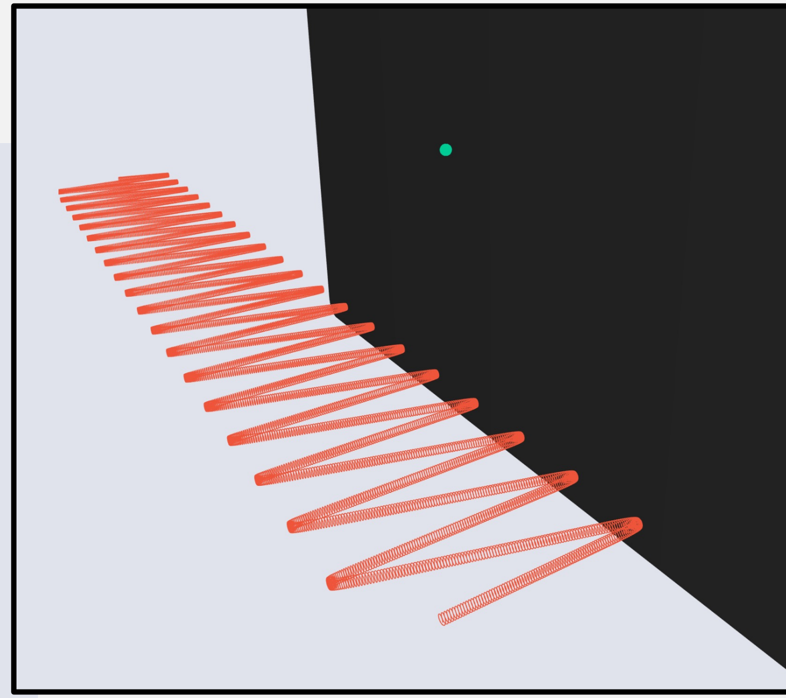
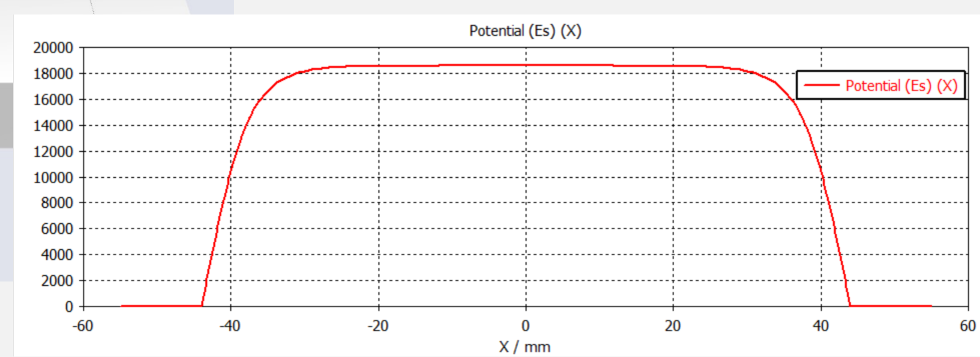
RF pick-up

Andi Tan (Princeton)







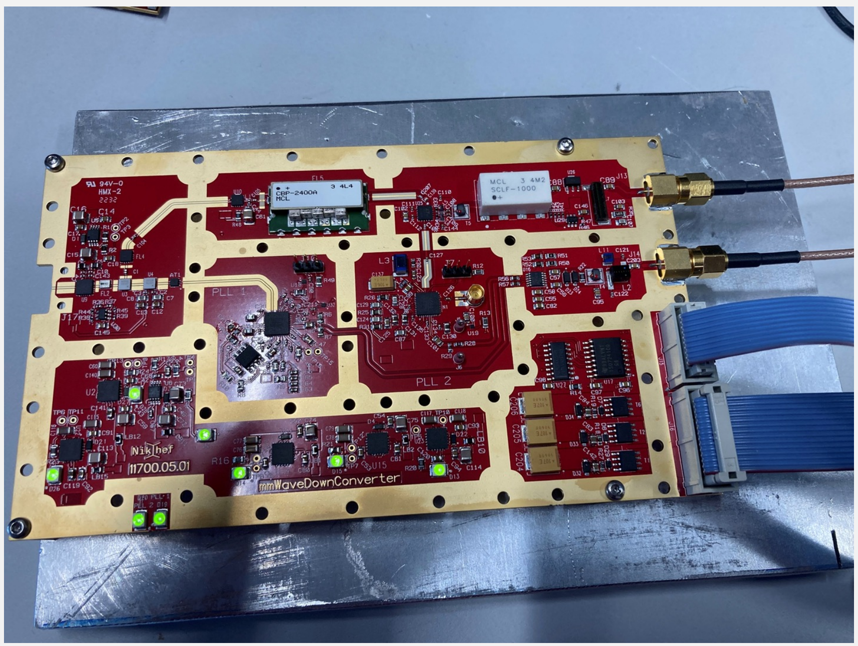
PROJECT 8 inspired

RF electronics

Downconverter

Input: RF signal (26 GHz)+high precision oscillator

Output: down-sampled signal at around 1 GHz



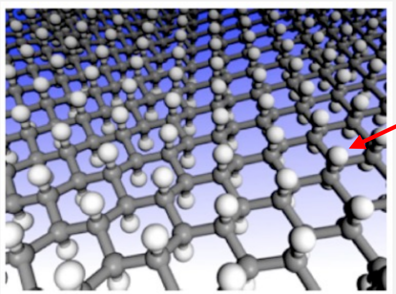
FPGA for online signal processing (online FFT)

Nikhef

Target: Tritium on graphene

PTOLEMY

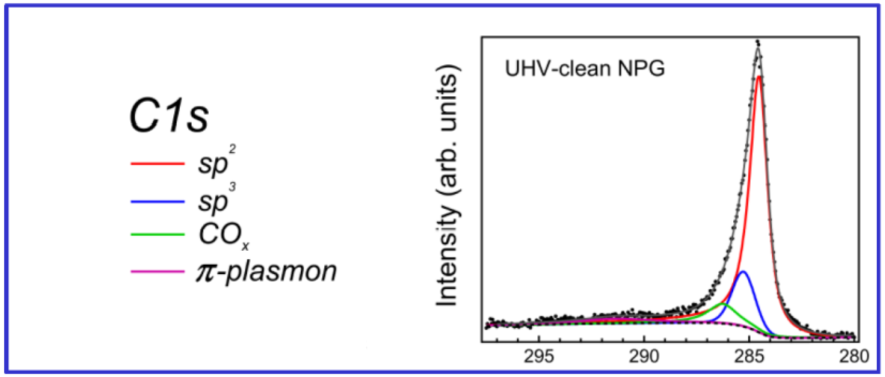
atomic H as a tool to '*pinch*' the sp2 bonds towards an sp3 configuration while maintaining the planar nature of graphene



sp3 H-C bond

how to estimate the H (or D):C upload → directly from a quantification of the sp3 bond spectroscopic signal from the XPS C 1s core level:

$$\%H/C = I_{sp3} / (I_{sp3} + I_{sp2}) = \Theta$$

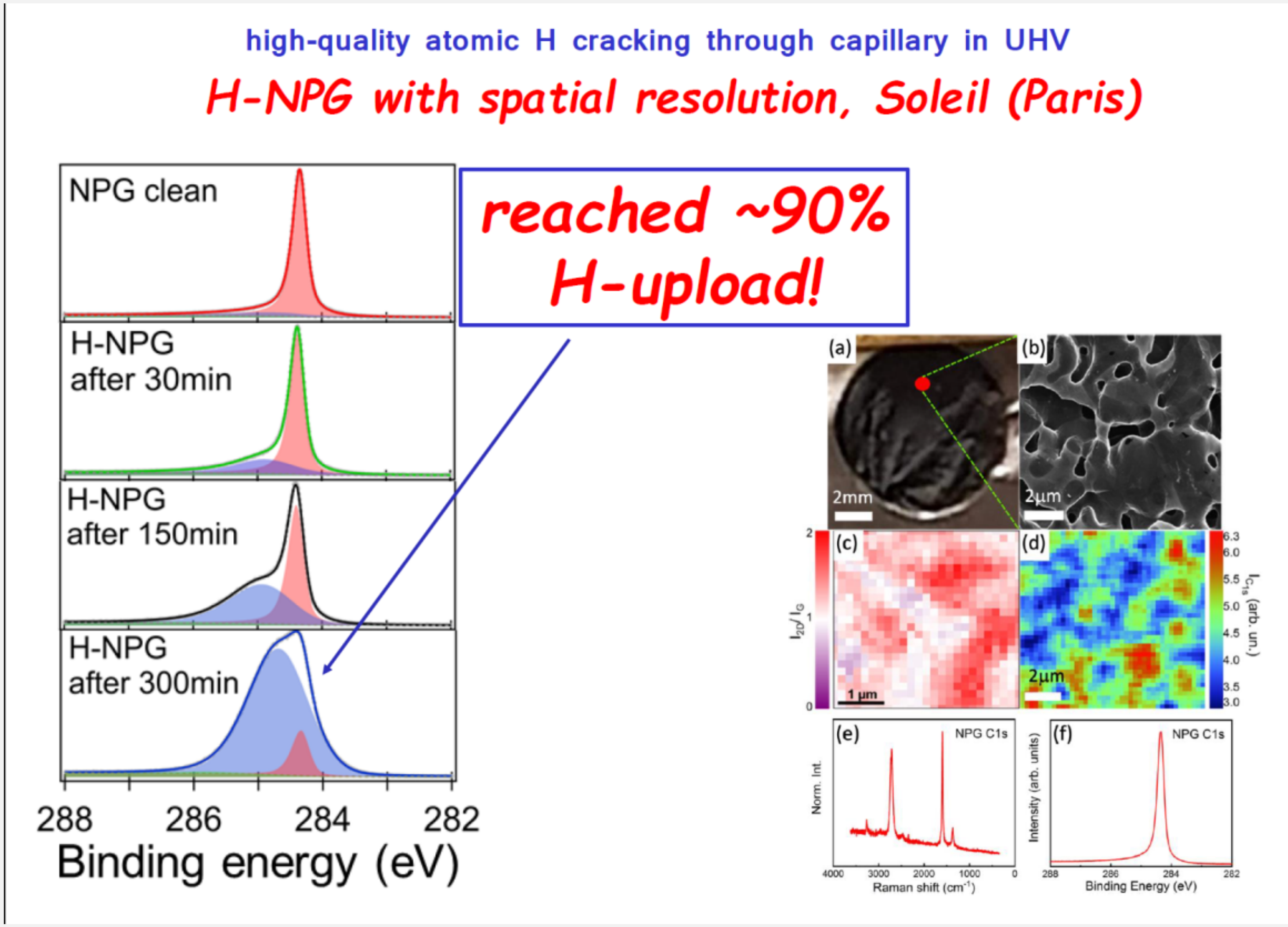


Abdelnabi et alii, Nanomat. **11**, 130 (2021)

H_2 flow into a capillary with hot-spot (~2000 C) in UHV → more than 95% molecules cracked in **atomic H** concentrated onto the sample

Hydrogen and Deuterium on (nanoporous) graphene

PTOLEMY



Betti et alii, Nano Lett. **22**, 2971 (2022)

Heisenberg effect

PTOLEMY

QUANTUM SPREAD

- Distributing tritium on flat graphene has one drawback

spatially localized tritium ⇨ uncertainty on tritium's momentum ⇨ spread in final electron energy

[Cheipesh, Cheianov, Boyarsky — PRD 2021, 2101.10069]

- A simple semi-classical estimate:

fluctuating momenta

$$\mathbf{p}_T = \Delta\mathbf{p}_T$$

$$\mathbf{p}_{He} = \bar{\mathbf{p}}_{He} + \Delta\mathbf{p}_{He}$$

$$\mathbf{p}_e = \bar{\mathbf{p}}_e + \Delta\mathbf{p}_e$$

energy and momentum conservation returns

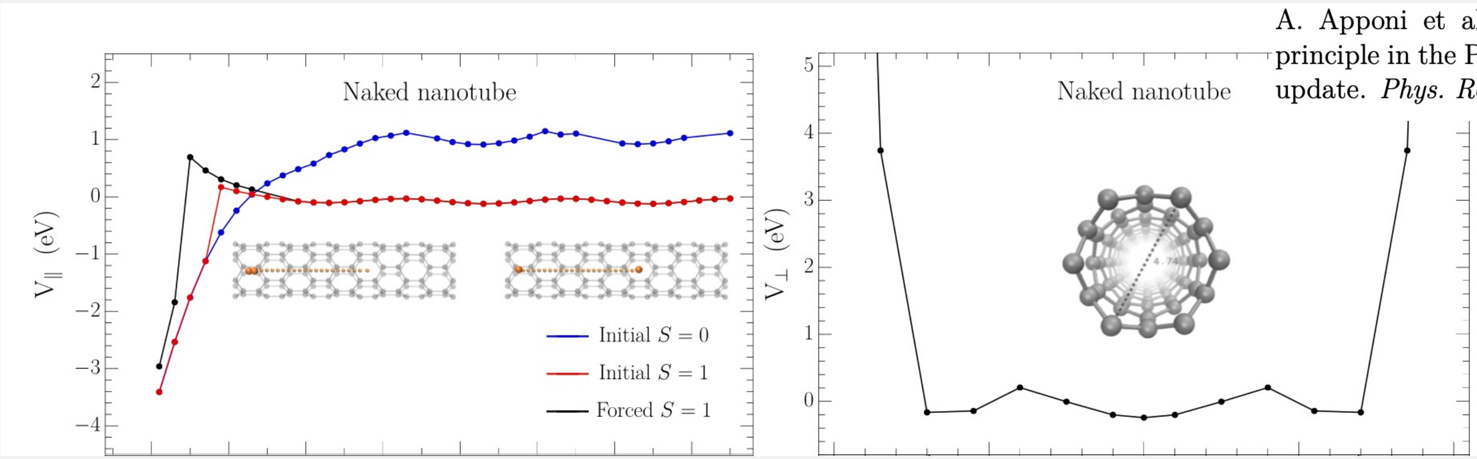
$$\Delta E_e \simeq \left| \frac{\mathbf{p}_e \cdot \Delta\mathbf{p}_T}{E_{He}} \right| \sim \frac{p_e}{m_{He}} \frac{1}{\Delta x_T} \sim 0.6 - 0.8 \text{ eV}$$

spread of initial tritium wave function $\left(\Delta x_T \sim 0.1\,\text{Å}\right)$

an order of magnitude larger than the wanted energy accuracy

Alternative substrates

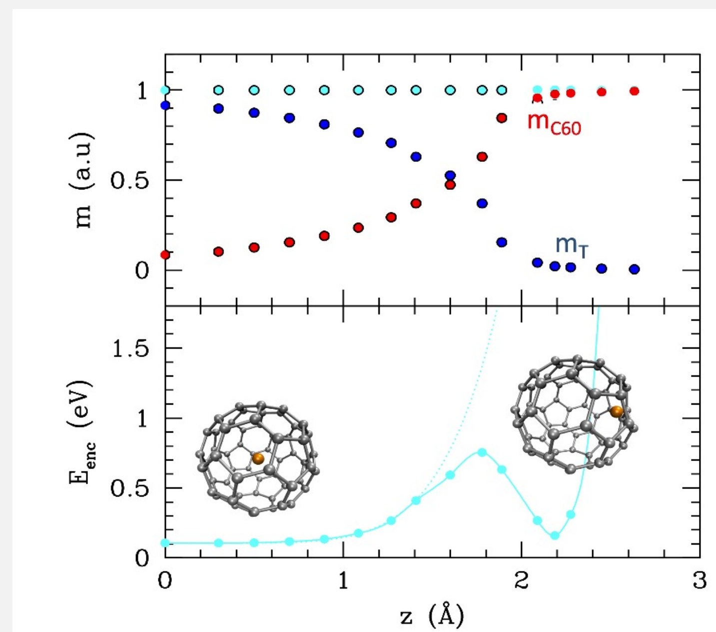
PTOLEMY



A. Apponi et al. Heisenberg's uncertainty principle in the PTOLEMY project: A theory update. *Phys. Rev. D*, 106(5):053002, 2022.

Concave substrate: flatter potential

- Carbon nanotubes
  - X and Y different
  - Recombination in the tubes
- Fullerenes



V. Tozzini (I. Nanoscienze)

Beyond Tritium?

PTOLEMY

O. Mikulenko, Y. Cheipesh, V. Cheianov, A. Boyarsky, arXiv:2111.09292 (2021)

Parent	$\tau_{1/2}$, [yr]	Daughter	Q, [keV]	$\gamma/\gamma_{^3H}$
^{171}Tm	1.92	^{171}Yb	96.5	0.110
^{63}Ni	101.	^{63}Cu	66.9	0.193
^{147}Pm	2.62	^{147}Sm	225.	0.188
^{151}Sm	90.0	^{151}Eu	75.9	0.107
^{241}Pu	14.3	^{241}Am	20.8	0.04

30x smaller cross-section
500x smaller cross-section

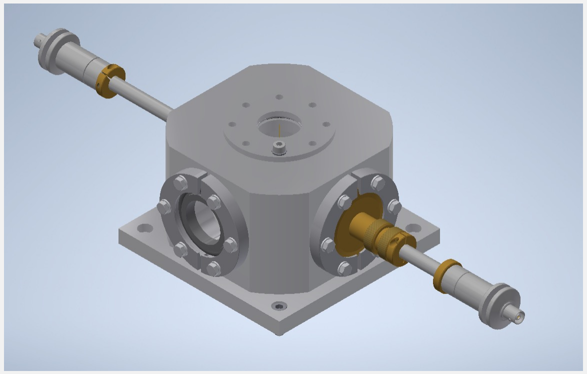
800x smaller cross-section

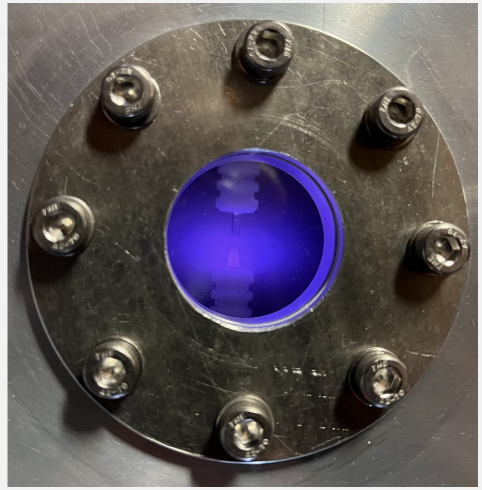
N. De Groot, J. Phy.s G50 055106 (2023)
DOI 10.1088/1361-6471/acc5fc

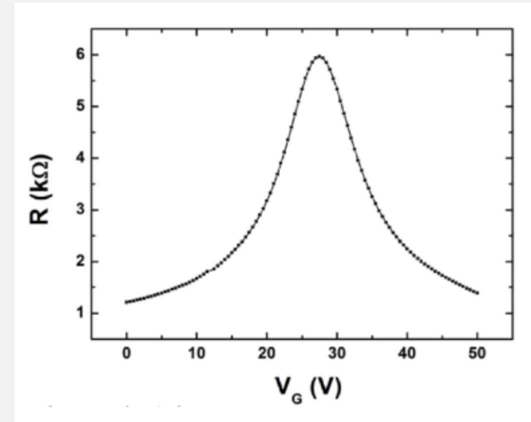
The bad news: 2 x 10^{-5} α-decay to ^{237}U which decays in 6 days to ^{237}Np, Q = 459 keV

- Use recoil ?
- Veto gammas from ^{237}U-decay
- Maybe gaseous target (PuF_6) with regeneration to filter Am and U for mass measurement
- Sterile neutrinos: Magneto-ν @LLNL (https://indico.cern.ch/event/1188759/contributions/5244403/)
- Not for solid target an CNB
- Tritium still the only serious option for relic neutrino detection!

Hydrogenation of Graphene

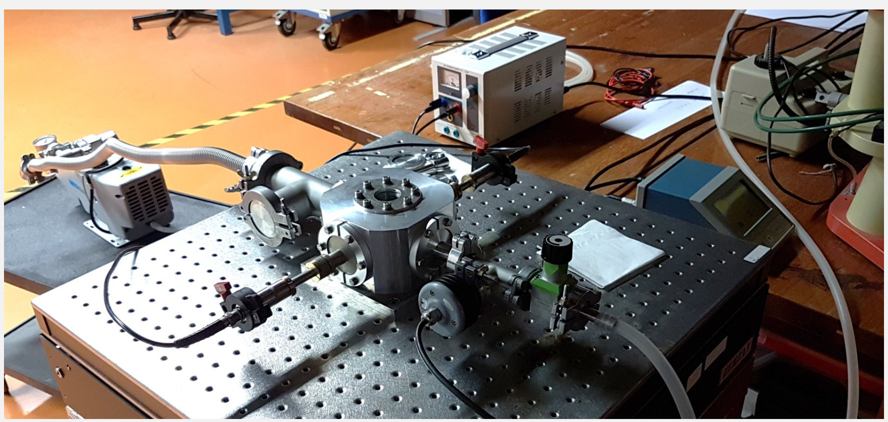




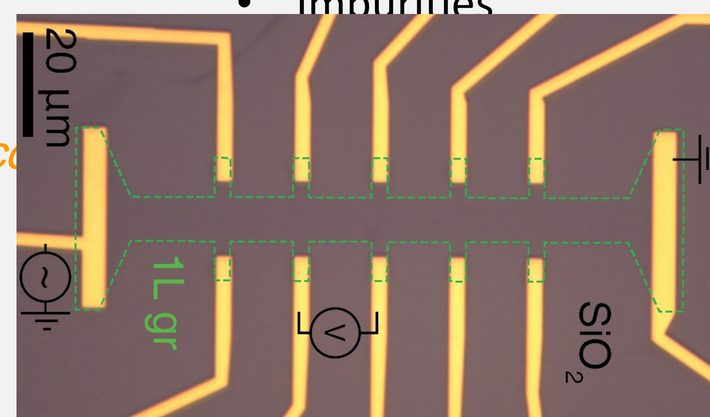


<u>Transfer Curve:</u>

- Gate voltage
- Electron mobility
- Temperature effect
- Charging efects
- Impurities



Au c

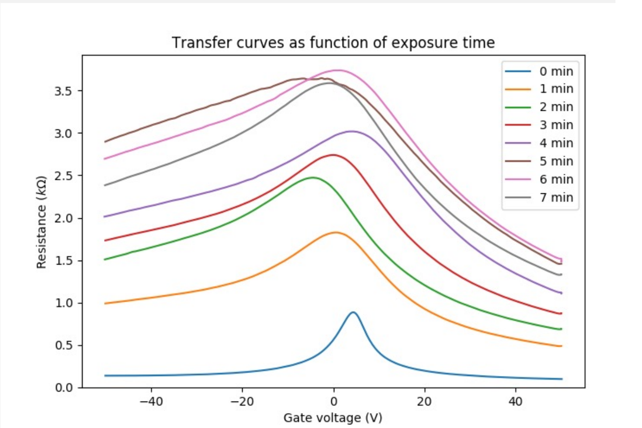


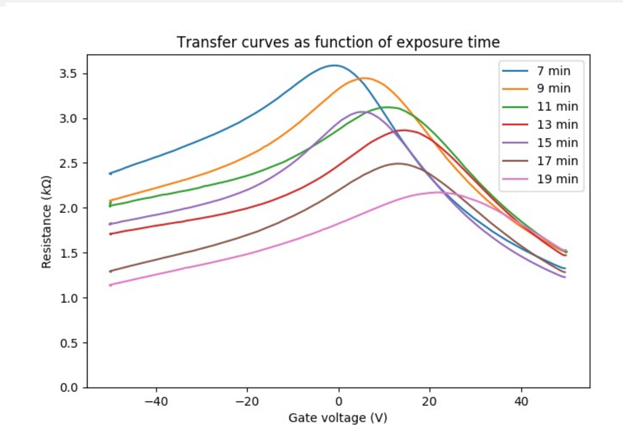
or

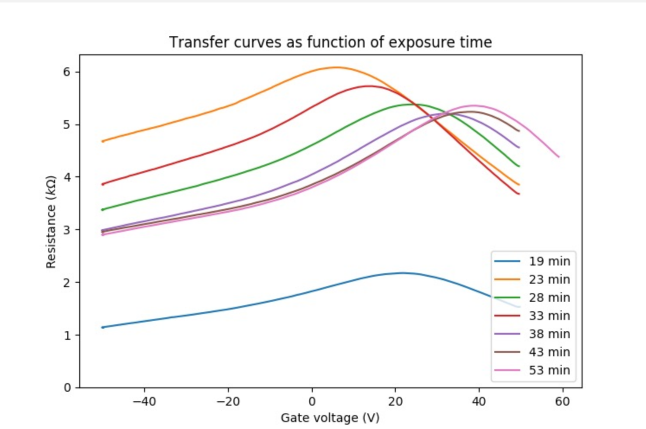
O. Zheliuk (Radboud)

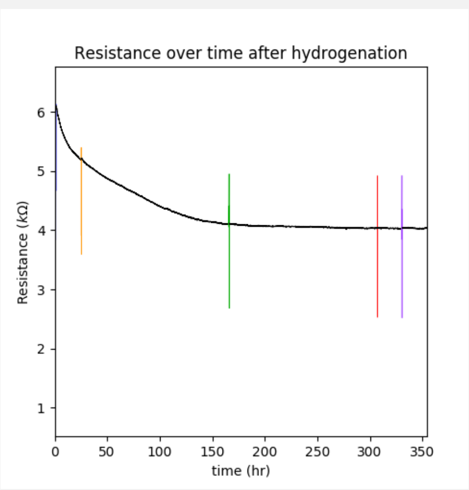
Hydrogenation of Graphene

PTOLEMY









- Work in process
- Many transient effects
- Annealing reduces resistance
- 180º removes contamination
- 400º removes hydrogen

Next: quantum hall, tritium, spectroscopy

KIT Karlsruher Institut für Technologie

Conclusions

PTOLEMY

- Ptolemy aims to measure the CNB
- An energy resolution of 50meV or better is required
- Many experimental challenges (target, RF, filter, calorimeter)
- Vibrant research programme
- Good progress towards demonstrator
- Many challenges still remain (target)
- Tritium still the best option, vital role for KIT

Many activities not covered