PTOLEMY

INFN
Laboratori Nazionali del Gran Sasso

UPDATE ON THE PTOLEMY PROJECT

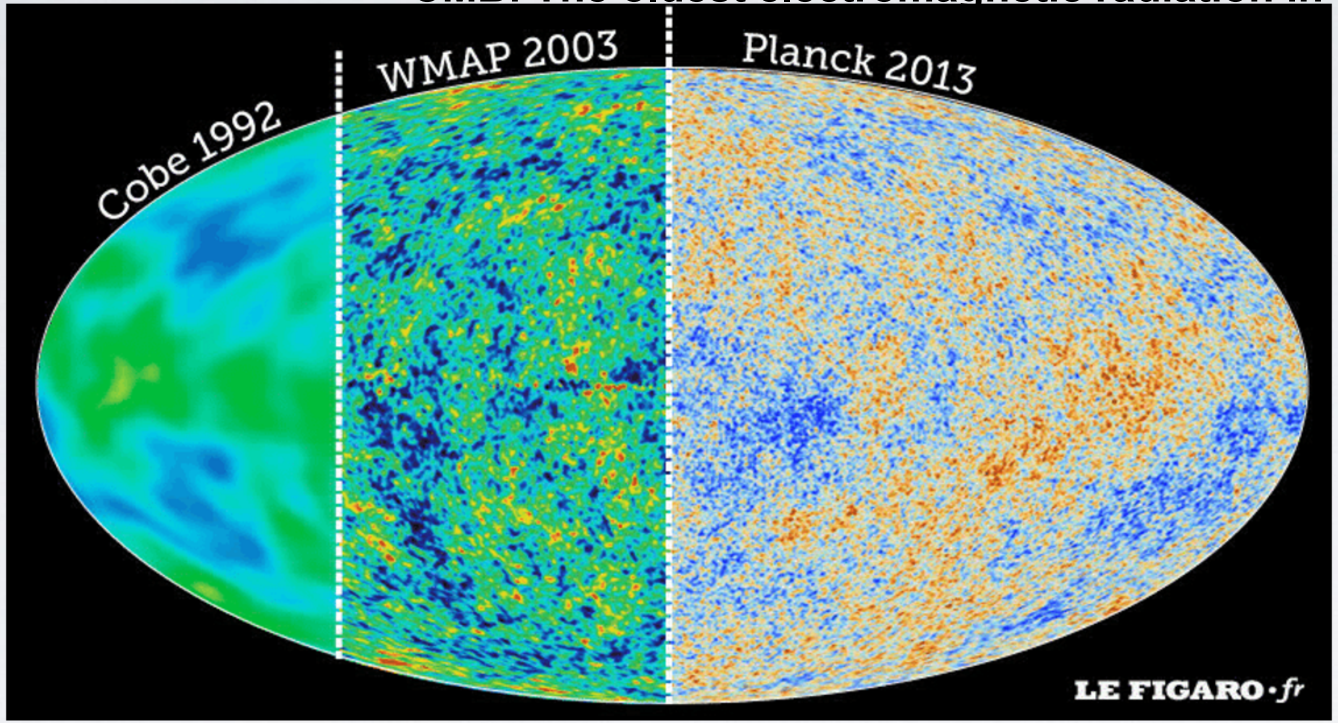
M MESSINA FROM LNGS AT NOW2022 WORKSHOP ON BEHALF OF THE PTOLEMY COLLABORATION, OSTUNI, SPTEMBER 2022

OUTLINE

- Short physics introduction
- PTOLEMY detector concept
- Conclusion and Outlook

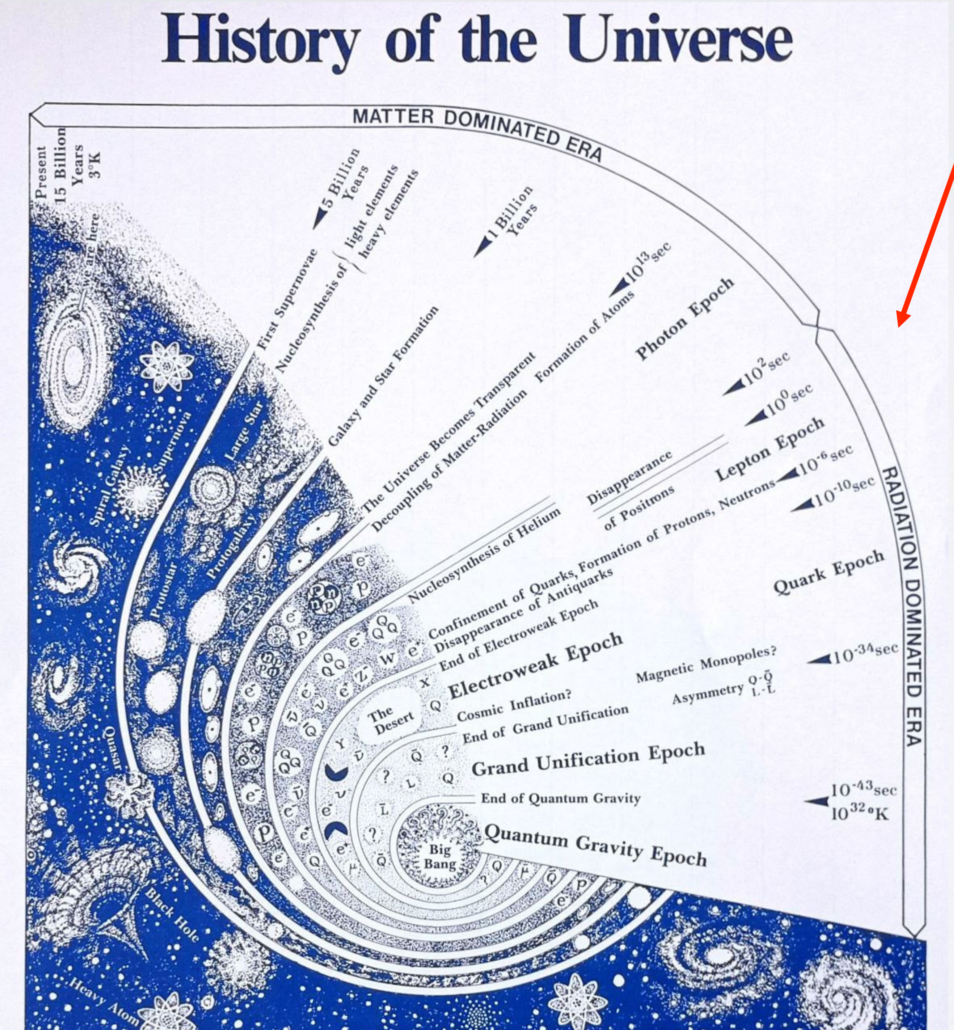
The Gold-mine of Cosmologist

CMB: The oldest electromagnetic radiation in the universe



- Universe is **expanding**: Hubble's law: $v = H_0 D$ (~70 km/s/Mpc), 1919.
- **Cosmic microwave background, Penzias & Wilson, 1964**
- **Abundance of primordial elements: ^{4}He, ^{2}H, ^{7}Li (?)**
- **Galaxies morphology** and stars populations in time
- **Primordial gas cloud** (without heavy elements), 2011

The Big Bang



ν decoupling **The present Universe emerges from an Ultra-dense and high temperature initial state**

Time of decoupling:
1 second
neutron/proton ratio
@start of nucleosynthesis
Temperature:
T_ν=1.95 K
Number density:
n_ν=112/cm^3
Velocity distribution:
$\langle v_\nu \rangle \sim T_\nu/m_\nu$

NEUTRINO FEATURES

- What we do know about neutrinos:

they are massive

well measured Δm_i^2

cosmic neutrino background
should be out there

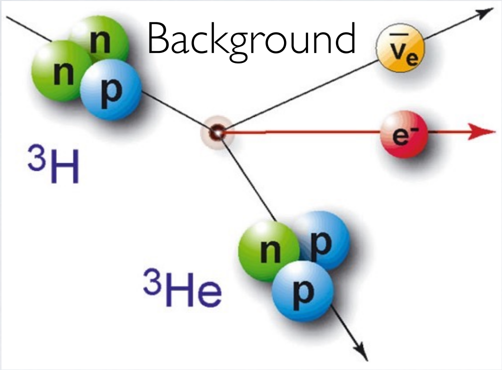
- What we don't know about neutrinos:

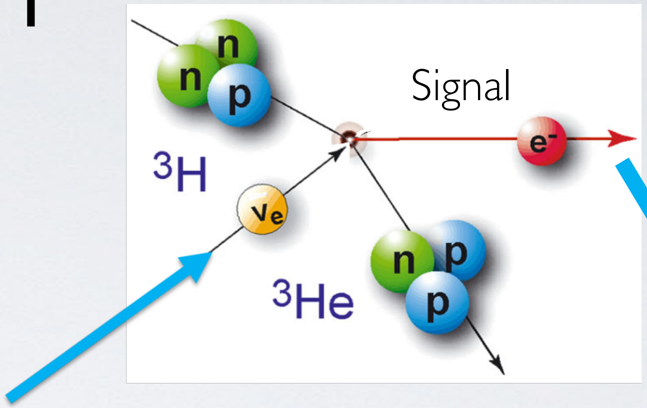
absolute mass
scale
$(m_\nu < 0.8 eV)$
[KATRIN — Nature Phys. 2022, 2105.08533]

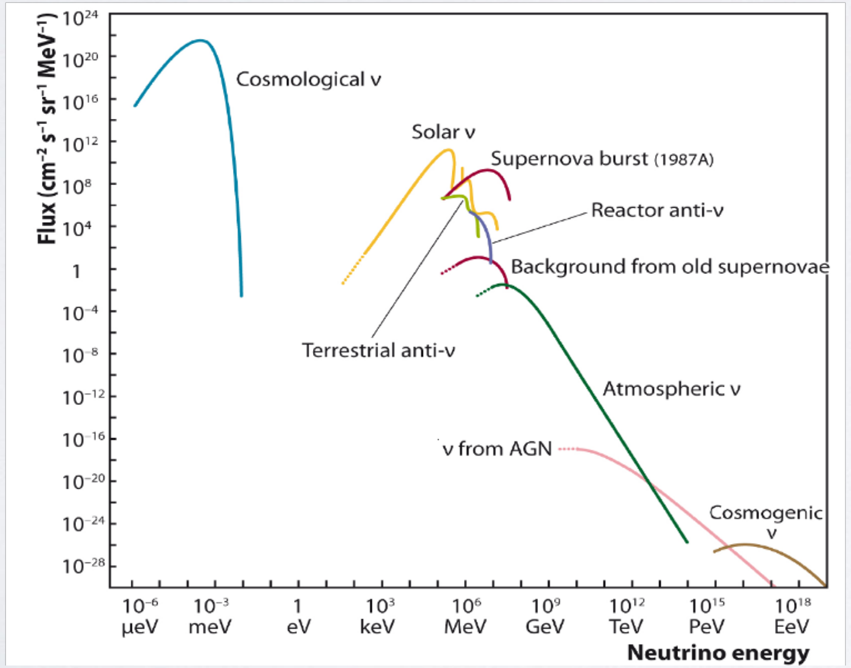
mass ordering
$(50_{meV} < m_{light} \simeq m_e\, or\, m_\tau)$
From Cosmology several
limits at 95 % CL on $\boldsymbol{\Sigma}$m$_{\boldsymbol{\nu}}$
from 0.56 to 0.11 eV

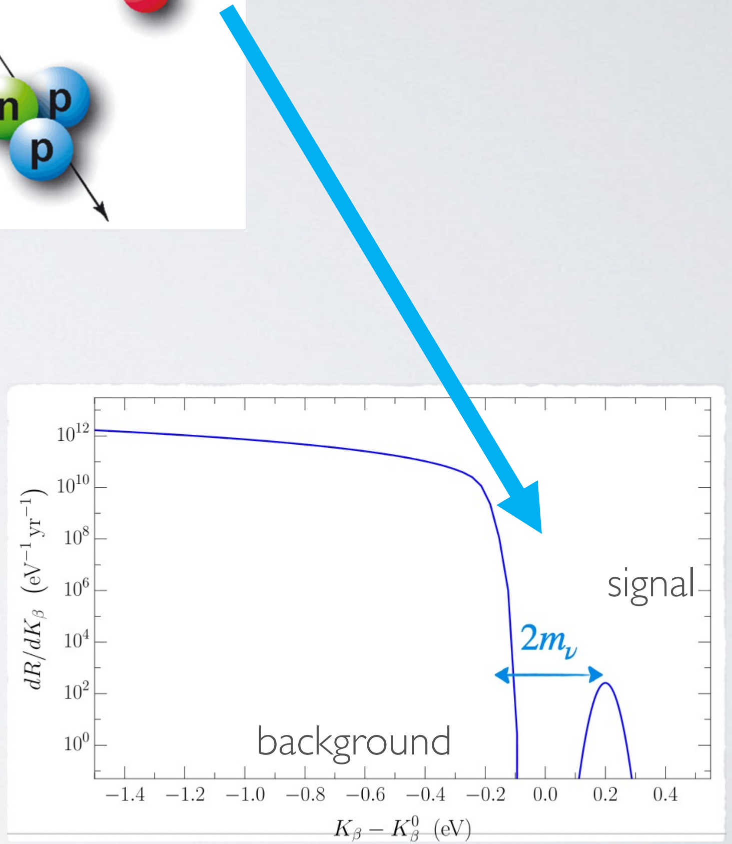
cosmic neutrino background
yet to be seen

PTOLEMY - RELIC NEUTRINO DETECTION STRATEGY









JCAP7-06-015

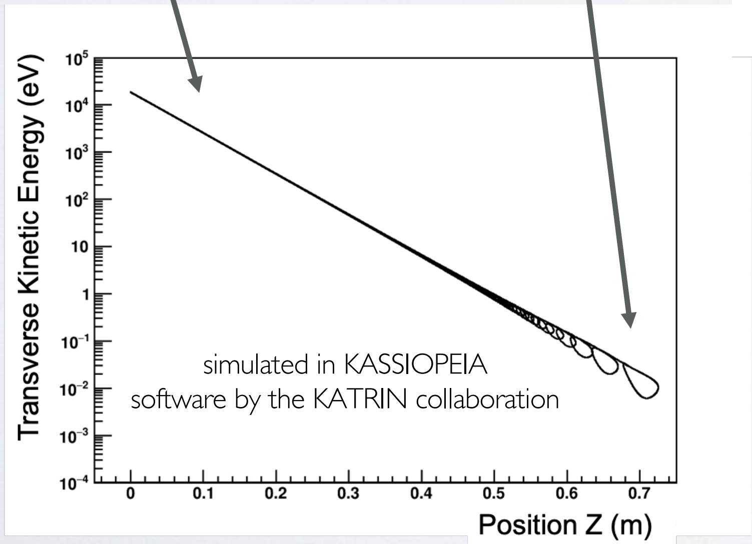
DETECTOR CONCEPT

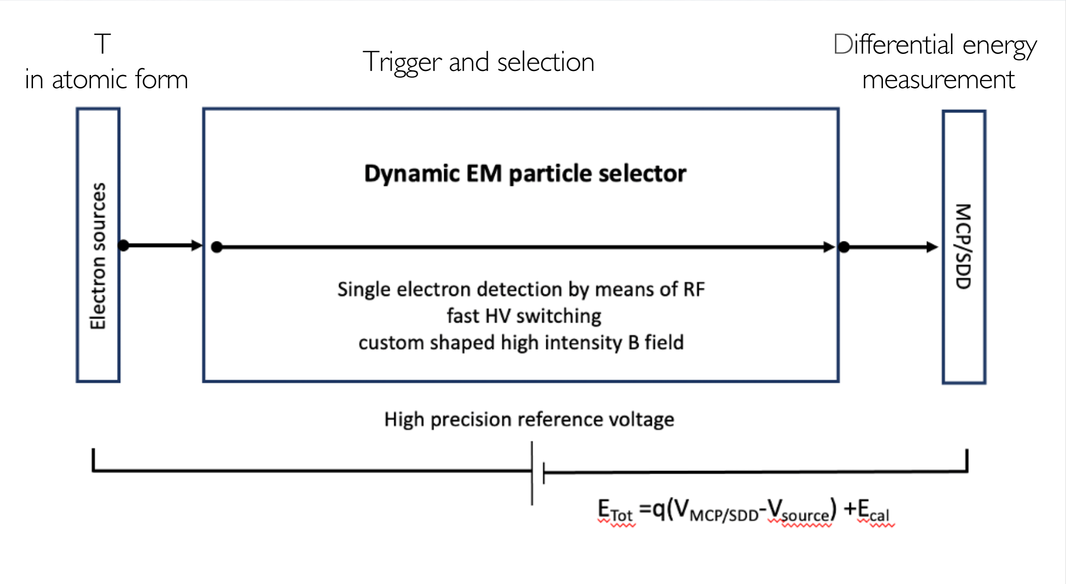
$$\frac{dT_\perp}{dt} = \frac{\mu}{B^2}\boldsymbol{E}\cdot(\boldsymbol{\nabla}B\times\boldsymbol{B})$$

Prog.Part.Nucl.Phys. 106 (2019) 120-131

New concept: **Transverse drift filter**

18.6 keV ➠ 0.01 keV in 0.7 meters



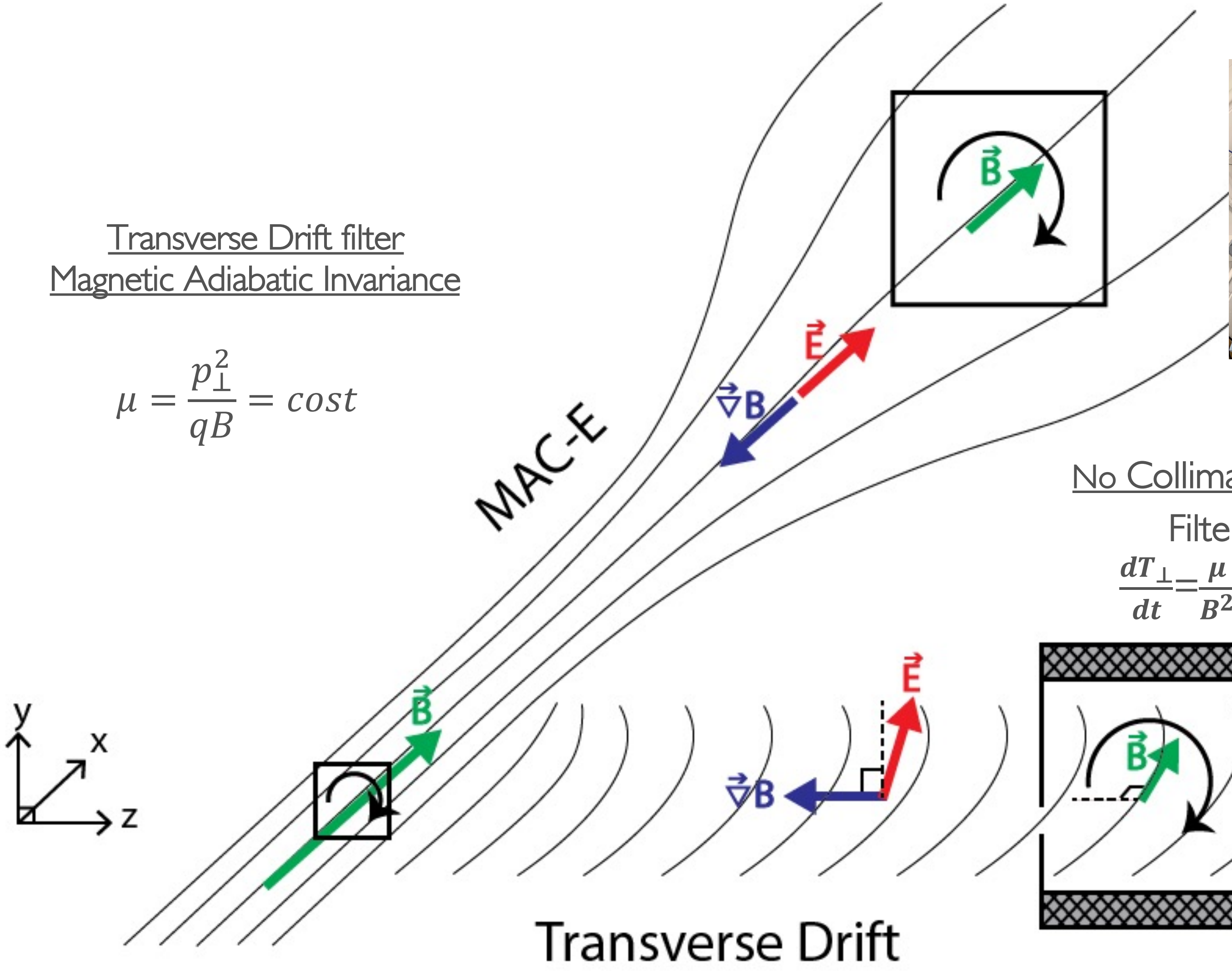


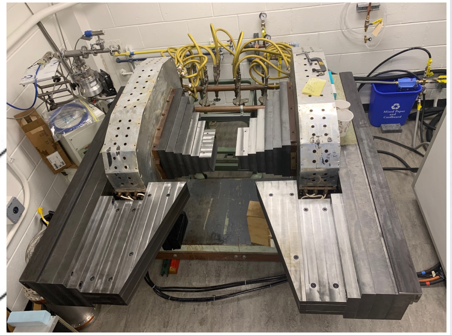
- PTOLEMY aims at using TES detectors with an envisaged resolution of $\Delta E \simeq 0.05\,eV$

ELECTROMAGNETIC FILTERS

Transverse Drift filter
Magnetic Adiabatic Invariance

$$\mu = \frac{p_\perp^2}{qB} = cost$$





PTOLEMY ~1m^3

No Collimation: $-\nabla B \perp B$

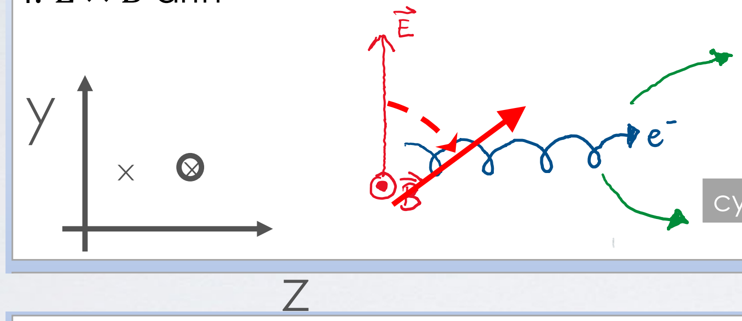
Filter (E-Field)

$$\frac{dT_\perp}{dt} = \frac{\mu}{B^2}\,\boldsymbol{E}\cdot(\nabla \boldsymbol{B} x \boldsymbol{B})$$

PTOLEMY FILTER CONCEPT

Auke Pieter Colijn (PATRAS 2019)

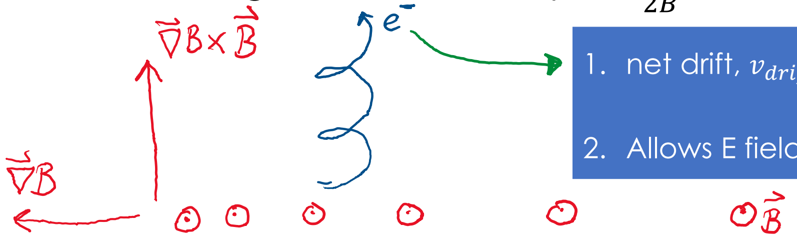
I: $\vec{E} \times \vec{B}$ drift



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

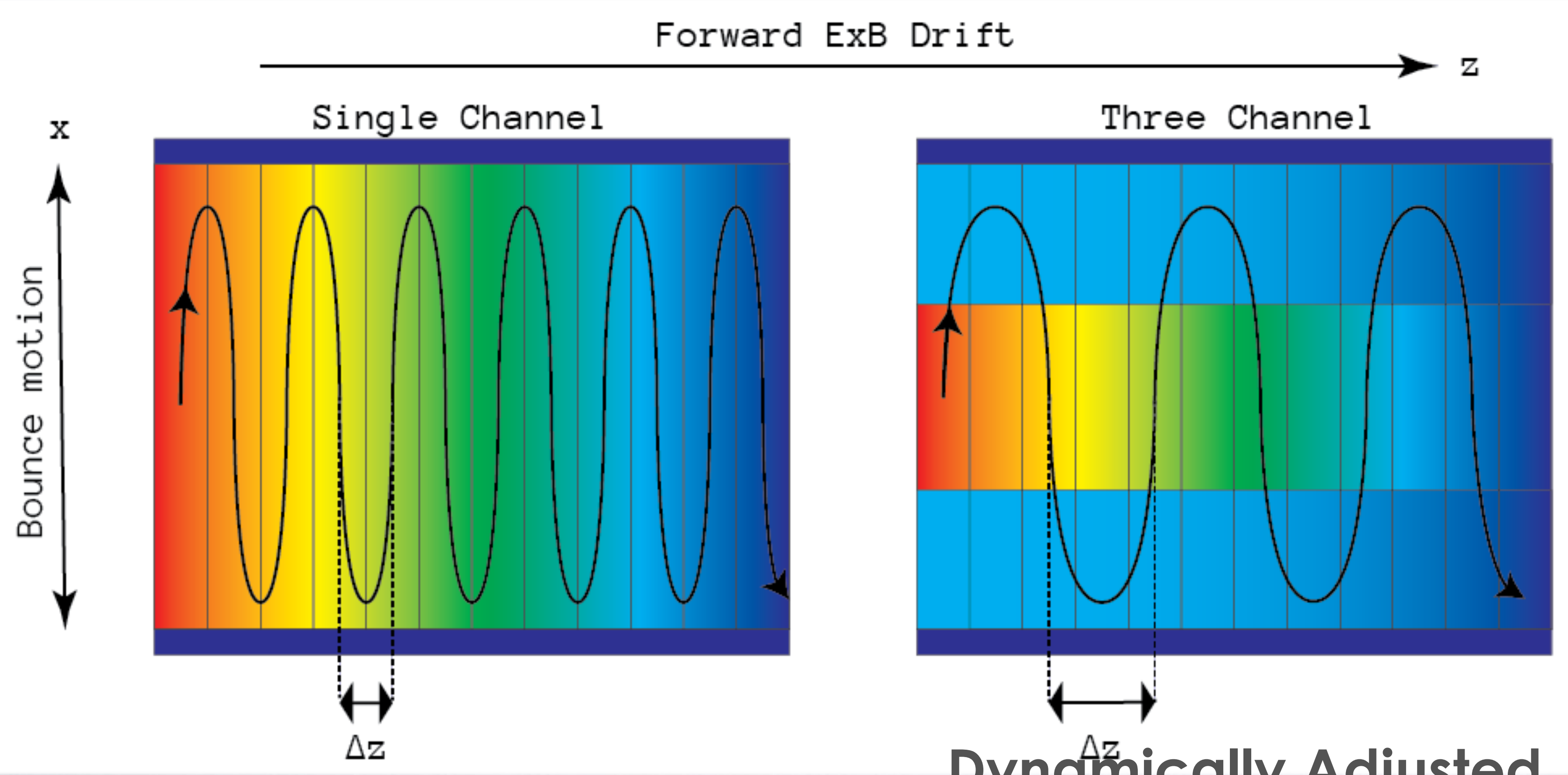
$$\boldsymbol{V}_{\nabla B}(z)|_{x,y=0} = -\frac{\boldsymbol{\mu} \times \boldsymbol{\nabla}_\perp \boldsymbol{B}(\boldsymbol{z})}{qB(z)}$$

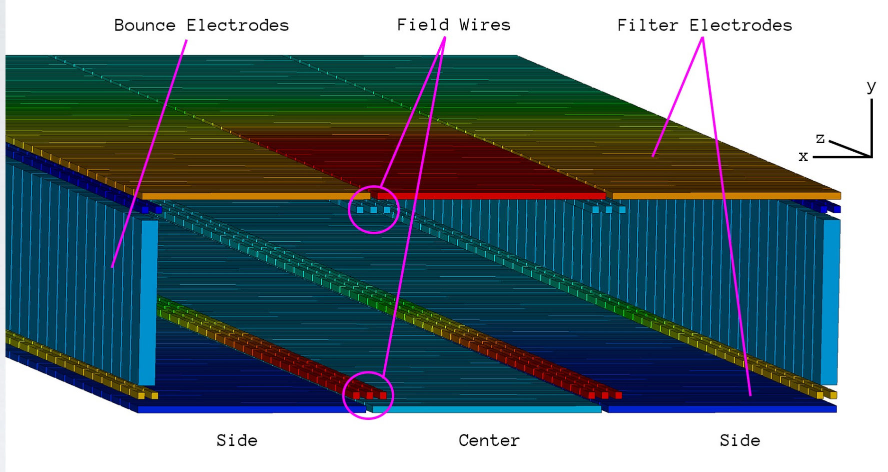
$$\boldsymbol{V}^y_{E\times B}(z)|_{x,y=0} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B_x^2} = \frac{E_z B_x \hat{\boldsymbol{y}}}{B_x^2} = \frac{E_z}{B_x}\hat{\boldsymbol{y}}$$

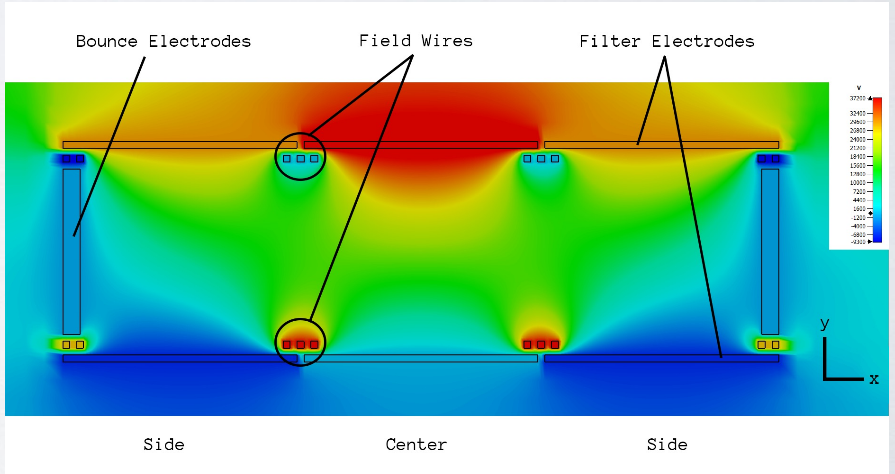
Enforce zero drift in y (rotate E):

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

BOBSLEDDING (PUSHING ELECTRON UP POTENTIAL)







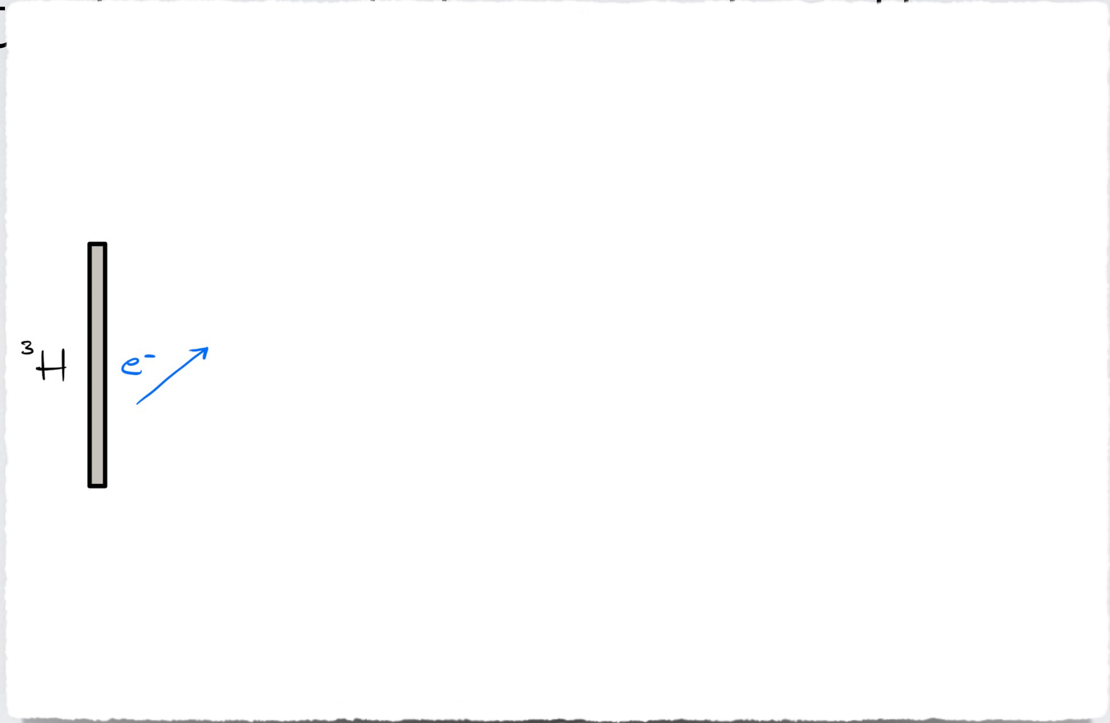
Transverse "Selector"
(one channel)

Dynamically Adjusted
(side channels)
to **Total Energy** "Selector"

PTOLEMY: THE IDEA

[see PTOLEMY – 1810.06703; PTOLEMY – JINST 2022, 2108.10388]

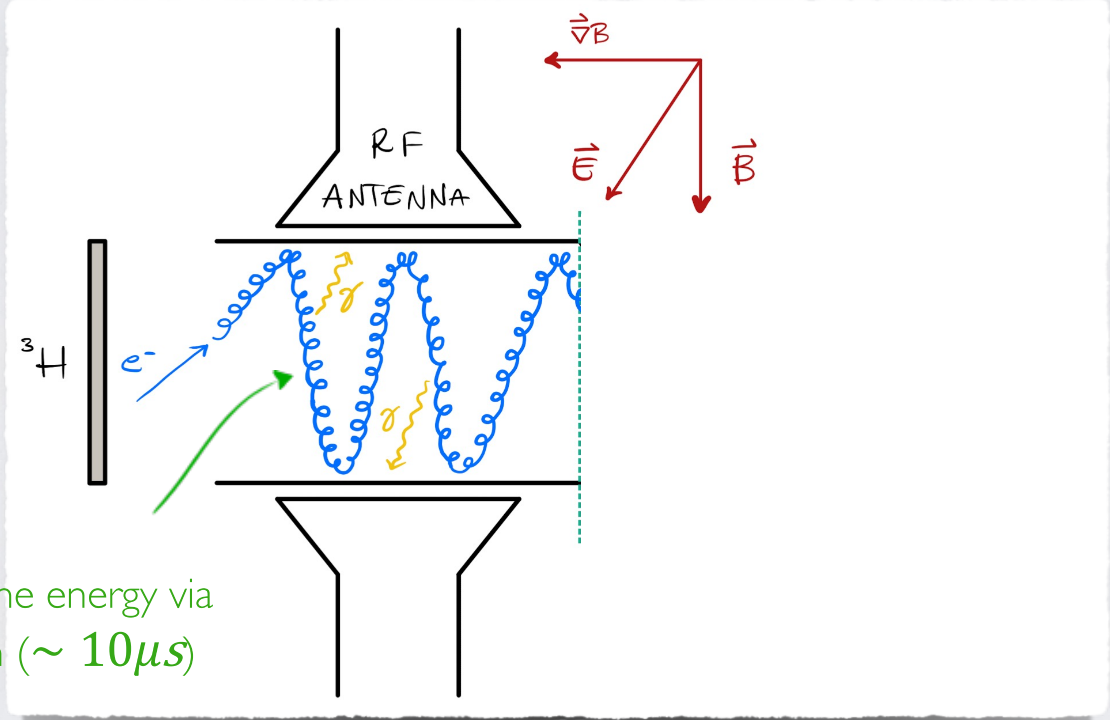
- A new electromagnetic filter idea based on RF det



PTOLEMY: THE IDEA

[see PTOLEMY – 1810.06703; PTOLEMY – JINST 2022, 2108.10388]

- A new electromagnetic filter idea based on RF detection and dynamic E setting

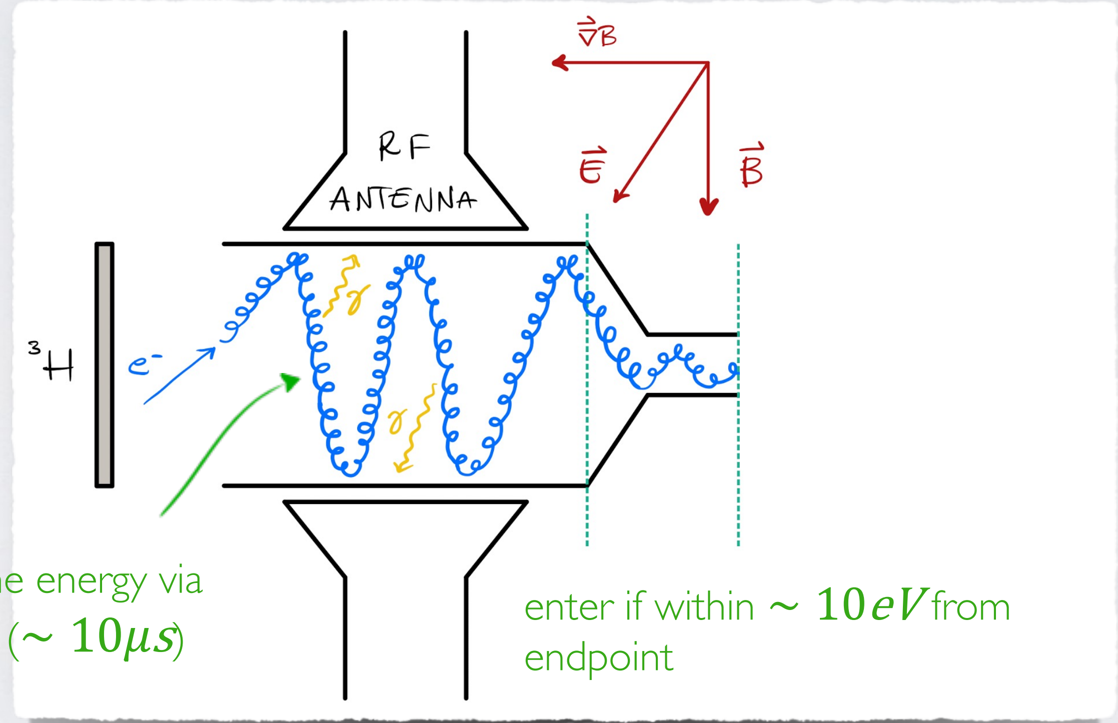


first measurement of the energy via cyclotron RF emission ($\sim 10\mu s$)

=

[see PTOLEMY — 1810.06703; PTOLEMY — JINST 2022, 2108.10388]

- A new electromagnetic filter idea based on RF detection and dynamic E setting



first measurement of the energy via cyclotron RF emission ($\sim 10\mu s$)

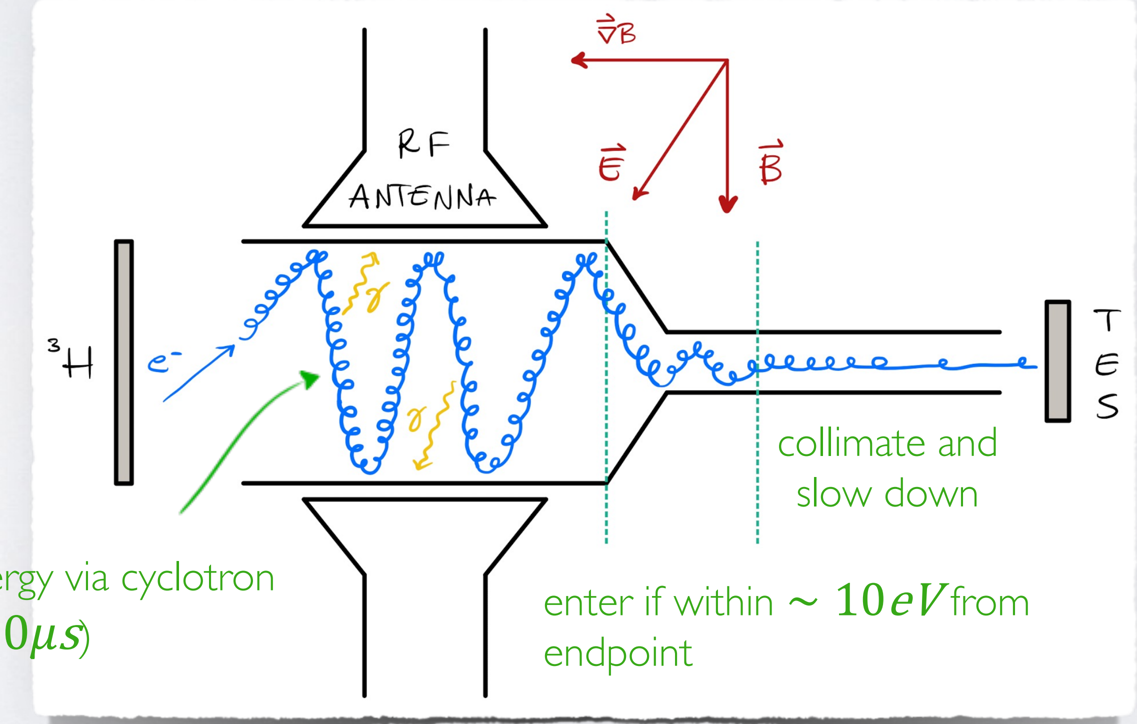
enter if within $\sim 10eV$ from endpoint

PTOLEMY: THE IDEA

[see PTOLEMY — 1810.06703; PTOLEMY — JINST 2022, 2108.10388]

- A new electromagnetic filter idea based on RF detection and dynamic E setting

ΔV known to 1 ppm precision



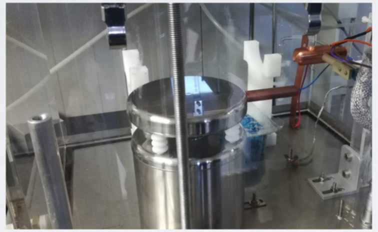
first measurement of the energy via cyclotron RF emission ($\sim 10\mu s$)

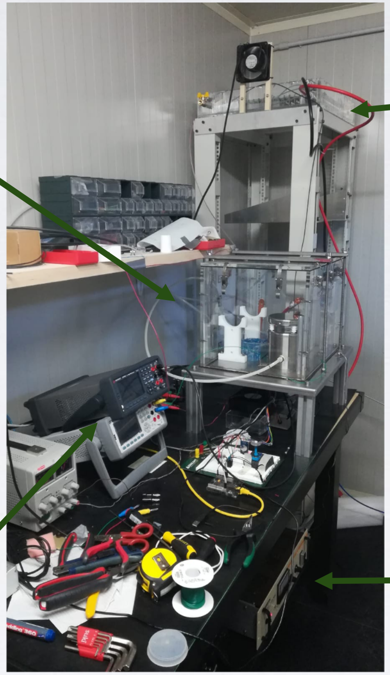
Many R&Ds
ongoing to
show the feasibility of the PTOLEMY detector

HV STABILITY AND MONITORING

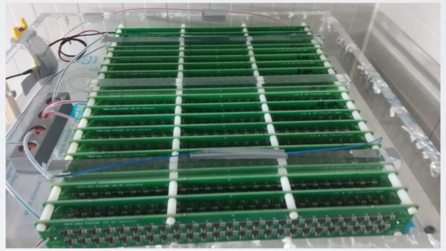
@LNGS

Field mill box





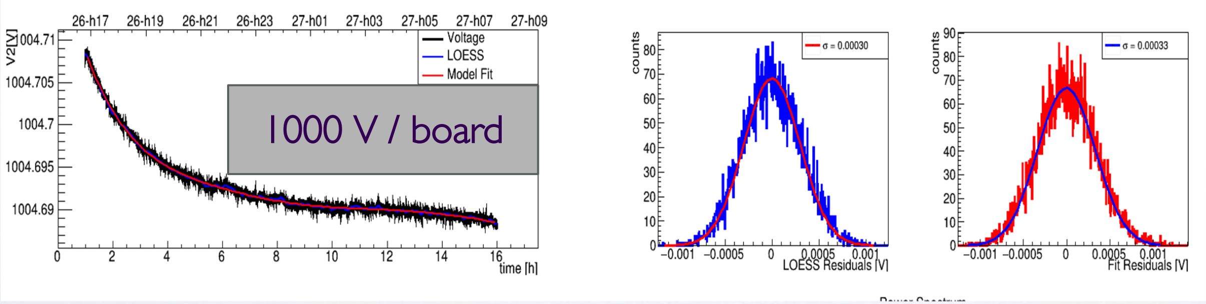
Diodes box



High precision voltmeter Keysight®

Power supply Bertan®

environmental parameter stabilization (dT ~ 0.1°C, Pressure < 1mBar, humidity 0%)



Single board
σ = 0.3 mV

Expect $\sqrt{N_{boards}}$:
~1.4mV@20kV

Field Mill ~50mV

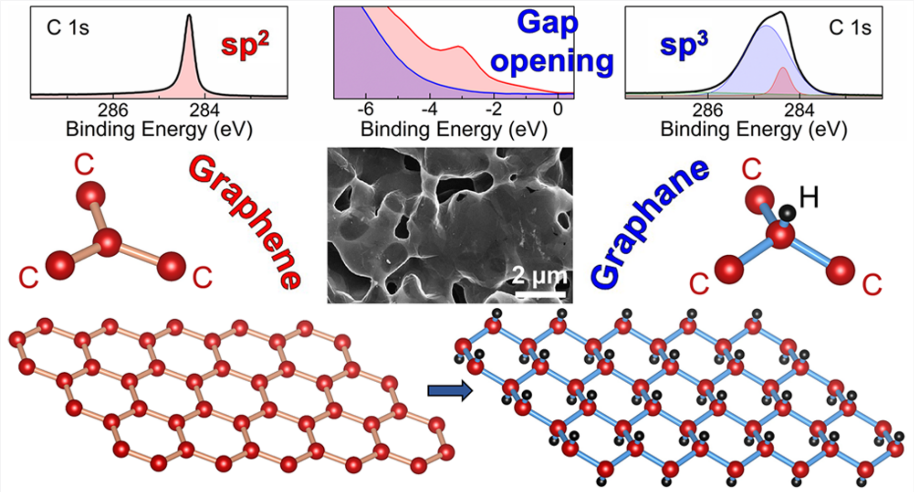
Gap Opening in Double-Sided Highly Hydrogenated Free-Standing Graphene

Maria Grazia Betti,* Ernesto Placidi, Chiara Izzo, Elena Blundo, Antonio Polimeni, Marco Sbroscia, José Avila, Pavel Dudin, Kailong Hu, Yoshikazu Ito, Deborah Prezzi,* Miki Bonacci, Elisa Molinari, and Carlo Mariani

Cite This: *Nano Lett.* 2022, 22, 2971–2977 Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: Conversion of free-standing graphene into pure graphane—where each C atom is sp^3 bound to a hydrogen atom—has not been achieved so far, in spite of numerous experimental attempts. Here, we obtain an unprecedented level of hydrogenation (≈90% of sp^3 bonds) by exposing fully free-standing nanoporous samples—constituted by a single to a few veils of smoothly rippled graphene—to atomic hydrogen in ultrahigh vacuum. Such a controlled hydrogenation of high-quality and high-specific-area samples converts the original conductive graphene into a wide gap semiconductor, with the valence band maximum (VBM) ∼ 3.5 eV below the Fermi level, as monitored by photoemission spectromicroscopy and confirmed by theoretical predictions. In fact, the calculated band structure unequivocally identifies the achievement of a stable, double-sided fully hydrogenated configuration, with gap opening and no trace of π states, in excellent agreement with the experimental results.

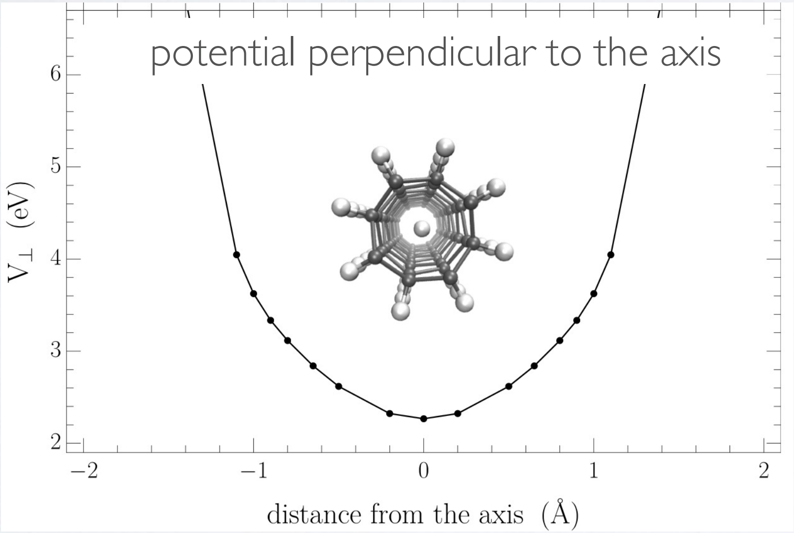


ALTERNATIVES

- Preliminary studies show that this is a feasible solution
- When passivated with hydrogen,

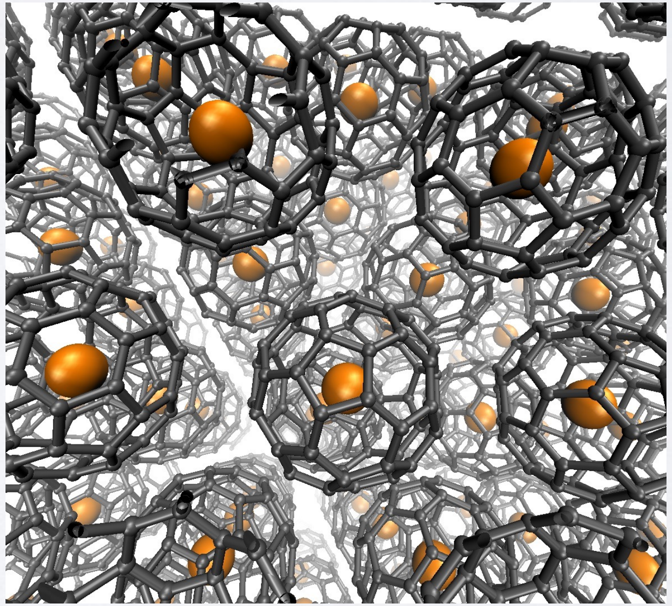
the nanotube potential looks like

[PTOLEMY — 2203.11228]



external B-field could also **prevent the formation of molecules** if two atoms are in the same nanotube

Fullerene sphere with **single T** atom
very promising even though prototypal idea



CALORIMETER

E_e=e(V_cal-V_target)+E_cal

Now: 0.11 eV @ 0.8 eV and 106 mK and 10x10 μm²
TiAuTi 90nm [Ti(45nm) Au(45nm)] (τ ~137 ns)

Design Goal (PTOLEMY): $\Delta E_{FWHM} = 0.05$ eV @ 10 eV

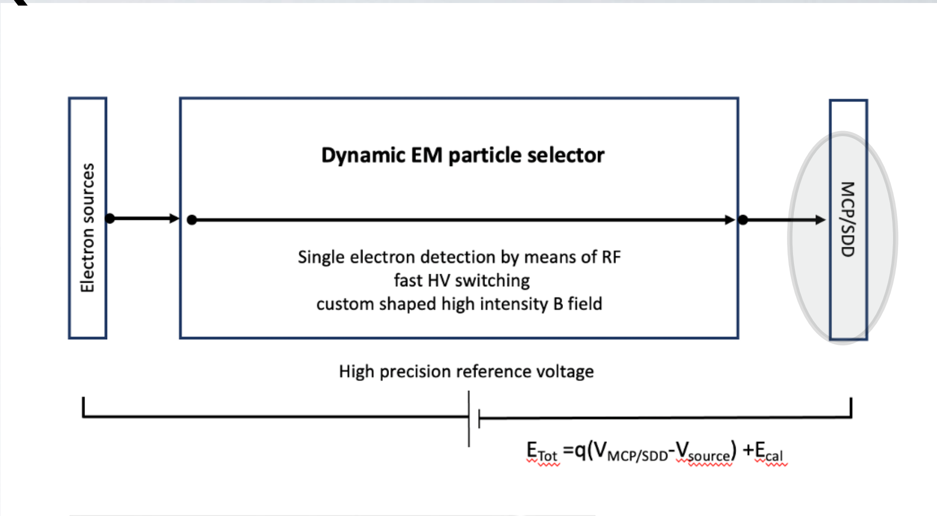
translates to $\Delta E \propto E^{\alpha}$ $(\alpha \leq 1/3)$

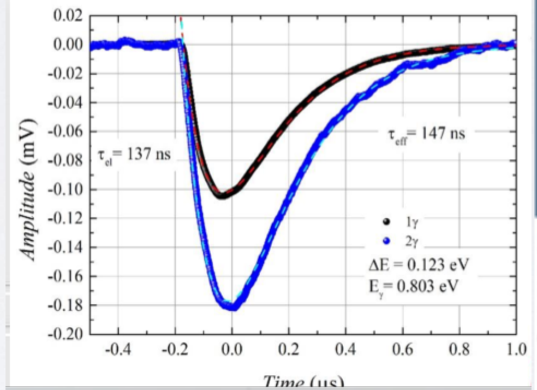
$\Delta E_{FWHM} = 0.022$ eV @ 0.8 eV

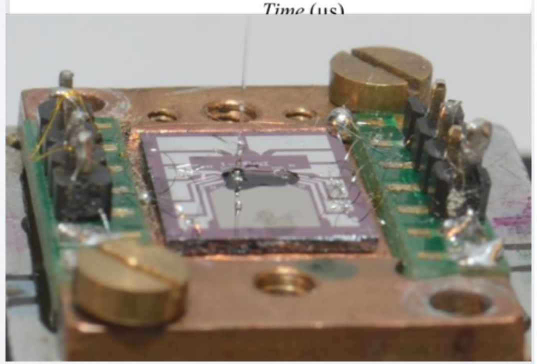
$$\Delta E_{FWHM} \approx 2.36 \sqrt{4 k_B T_c^2 \frac{C_e}{\propto} \sqrt{\frac{n}{2}}}$$

$\Delta E \propto T^{3/2}$ ⇨ T_c= 36 mK @10x10 μm² (t=90 nm)

⇨ T_c= 46 mK @10x10 μm² (t=45 nm)



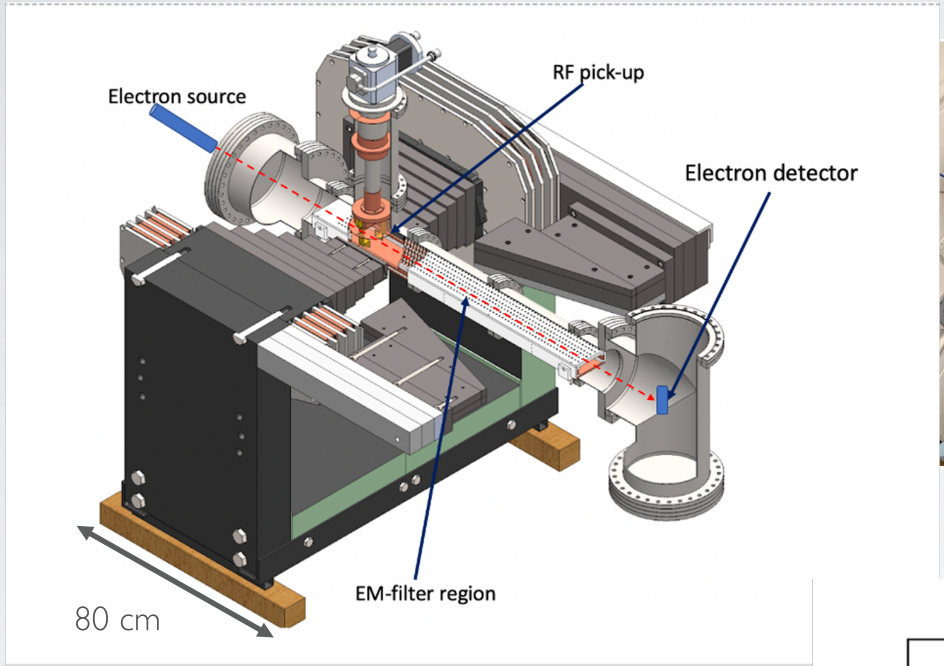


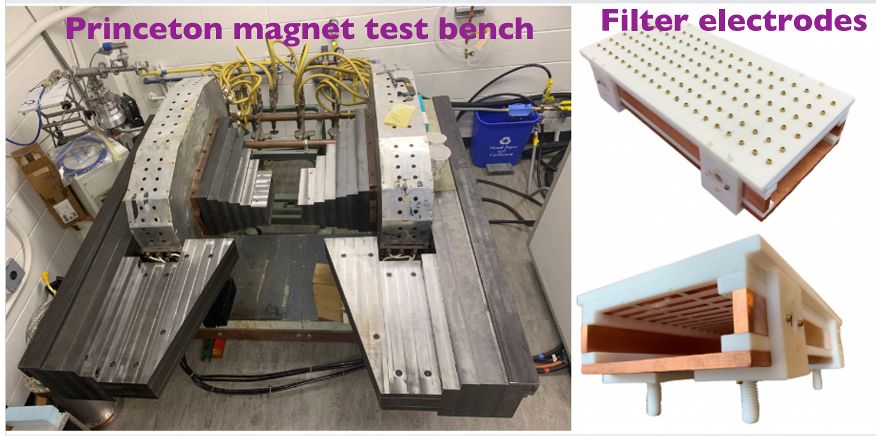


INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

DEMONSTRATOR MAGNET

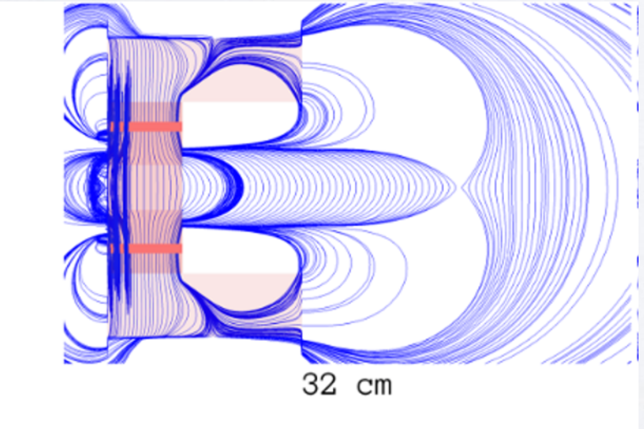
Being rebuilt at LNGS in a larger size.

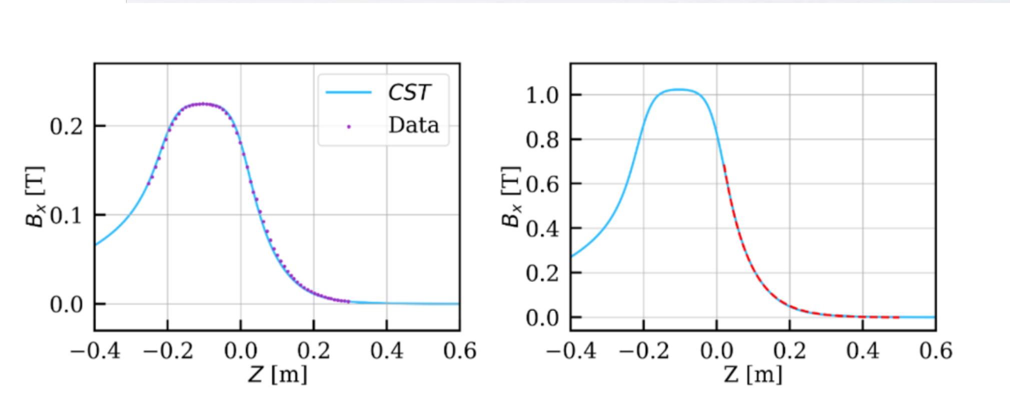




Measured B field shape as expected

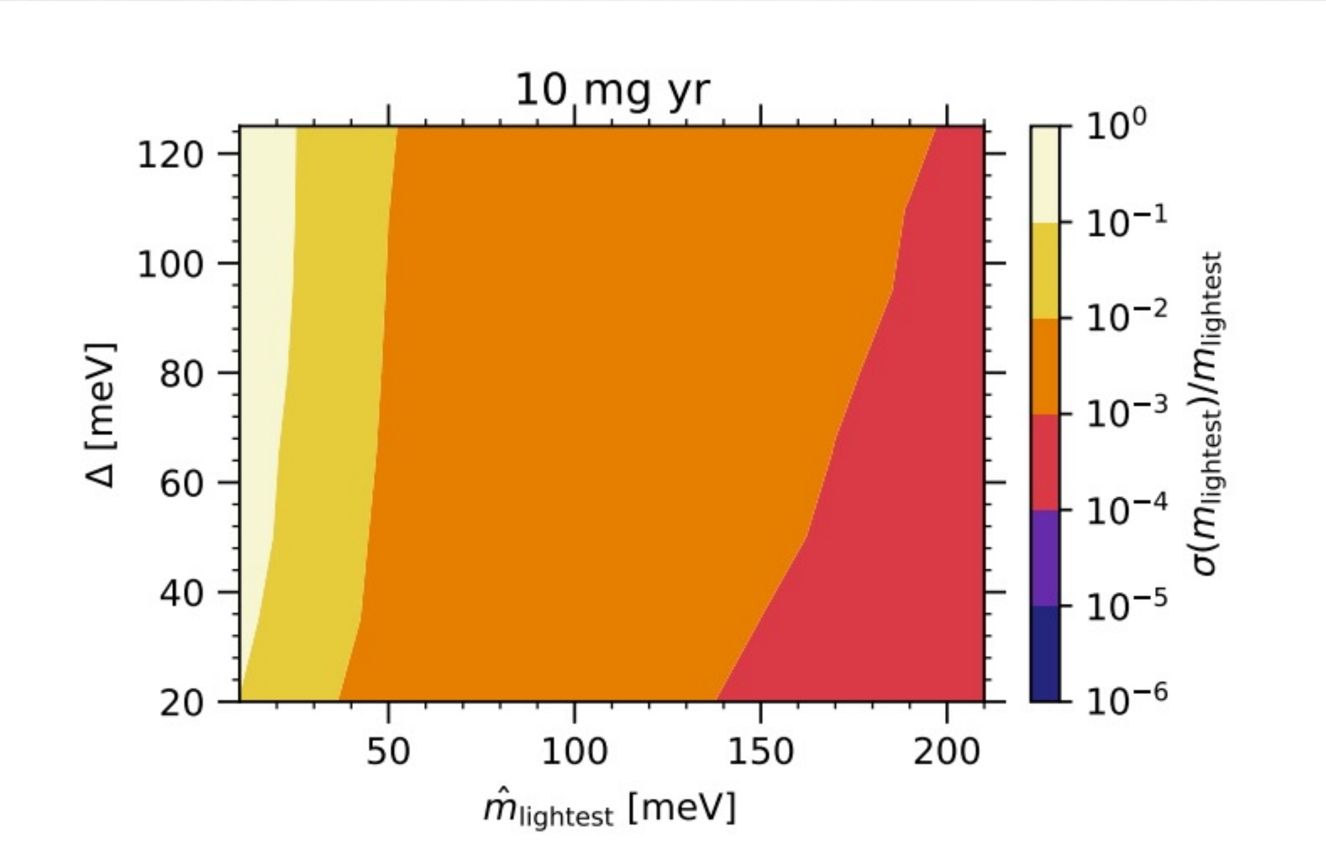
Simulated B-map





A taste of the results that PTOLEMY can achieve

Even in absence of capture events spectral analysis will allow to achieve mass measurement with the percentage uncertainty reported below: energy resolution versus lights neutrino mass for 10 mg x yr of exposures



Conclusion and Outlooks

- PTOLEMY aims at detecting cosmic neutrino background on a long term time scale
- The detector prototype will be ready at LNGS by next year
- Prototype baseline option is: T embedded on graphene; New concept EM filter in final configuration; electron energy resolution measured in several steps (MCP/SDD). Ultimately operate TES with sub-eV energy resolution.
- Possible intermediate results from Prototype on neutrino mass measurements
- Ultimate goals of demonstrator: instrumented mass ~ hundreds of μg, energy resolution 50-100 meV, T storage solution will come from optimisation of atomic T support structure. Time scale 5 years.

BACK UP

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 calculation returns

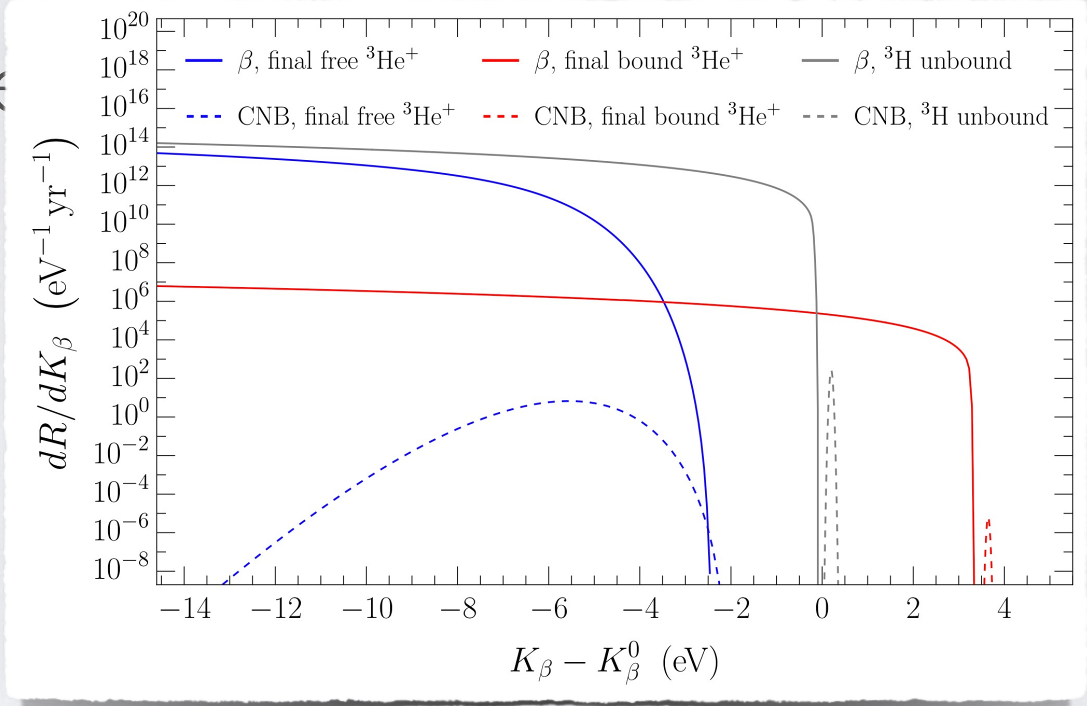
$$\Delta K_\beta = \left|\frac{\mathbf{p}_e \cdot \Delta \mathbf{p}_T}{E_{He}}\right| \sim \frac{p_e}{m_{He}} \frac{1}{\Delta x_T} \sim 0.6 - 0.8\, eV$$

spread of initial tritium wave function

an order of magnitude larger than the wanted energy accuracy

QUANTUM SPREAD

- A more accurate calculation for the rate, including differe

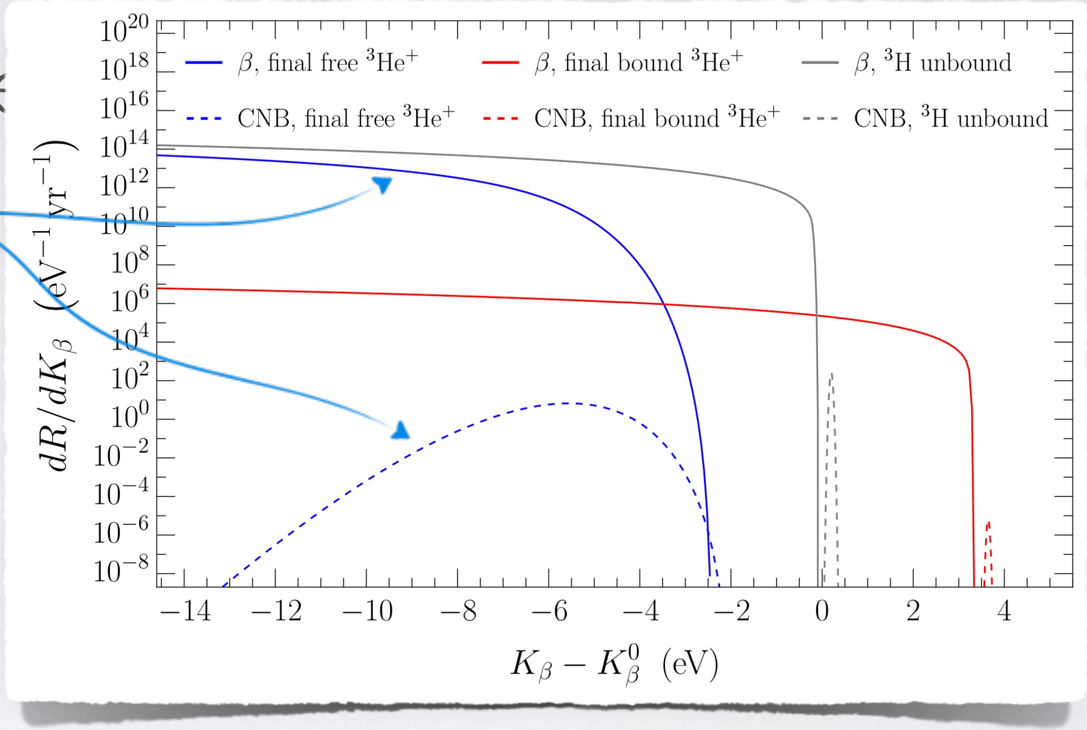


[PTOLEMY – 2203.11228]

QUANTUM SPREAD

- A more accurate calculation for the rate, including differe

$^3He^+$ **is mostly freed** from the graphene → the **cosmic neutrino peak disappears** under the decay spectrum

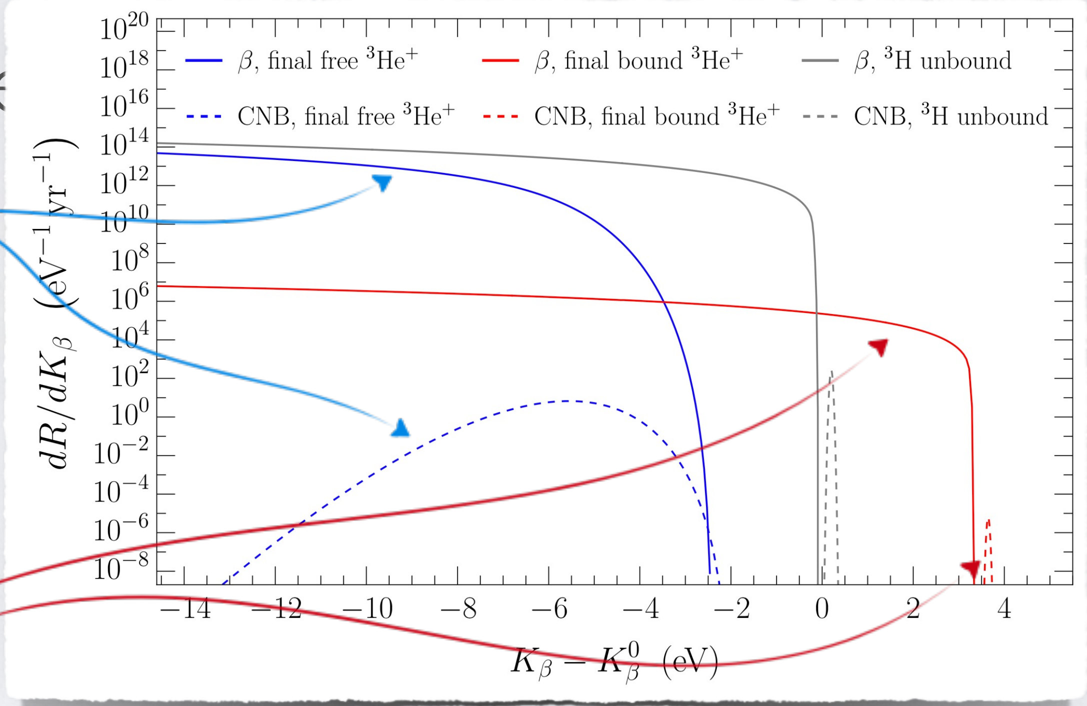


[PTOLEMY — 2203.11228]

QUANTUM SPREAD

- A more accurate calculation for the rate, including differe

$^3He^+$ **is mostly freed** from the graphene the **cosmic neutrino peak disappears** under the decay spectrum



When the $^3He^+$ **remains bound in the ground state** the peak is well separated it is however **exponentially unlikely**

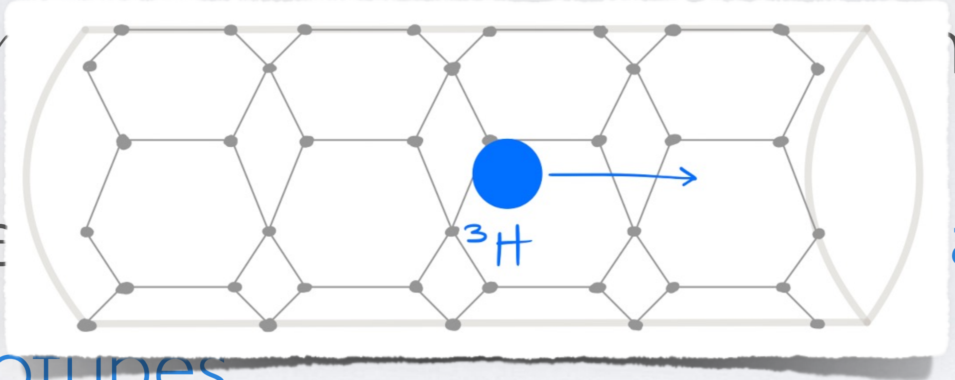
[PTOLEMY – 2203.11228]

A POSSIBLE SOLUTION

- To reduce the quantum spread we need to delocalize the initial tritium ($\Delta x_T \sim few Å$ should be enough) $\rightarrow$ try to realize an approximate momentum eigenstate

A POSSIBLE SOLUTION

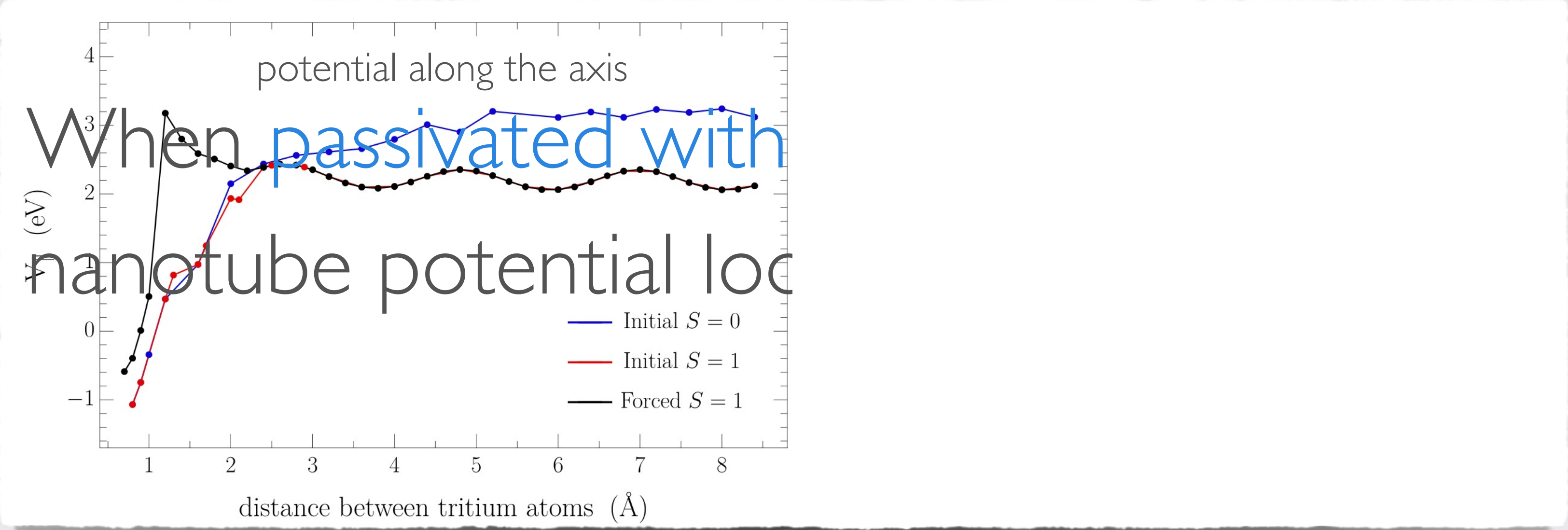
- To reduce the quantum spread we need to delocalize the initial tritium ($\Delta x_T \sim few$Å should be enough) try to realize an [PTOLEMY – 2203.11228] appr nstate



- One arbon nanotubes

A POSSIBLE SOLUTION

- Preliminary studies show that this is a feasible solution
- When passivated with nanotube potential loc

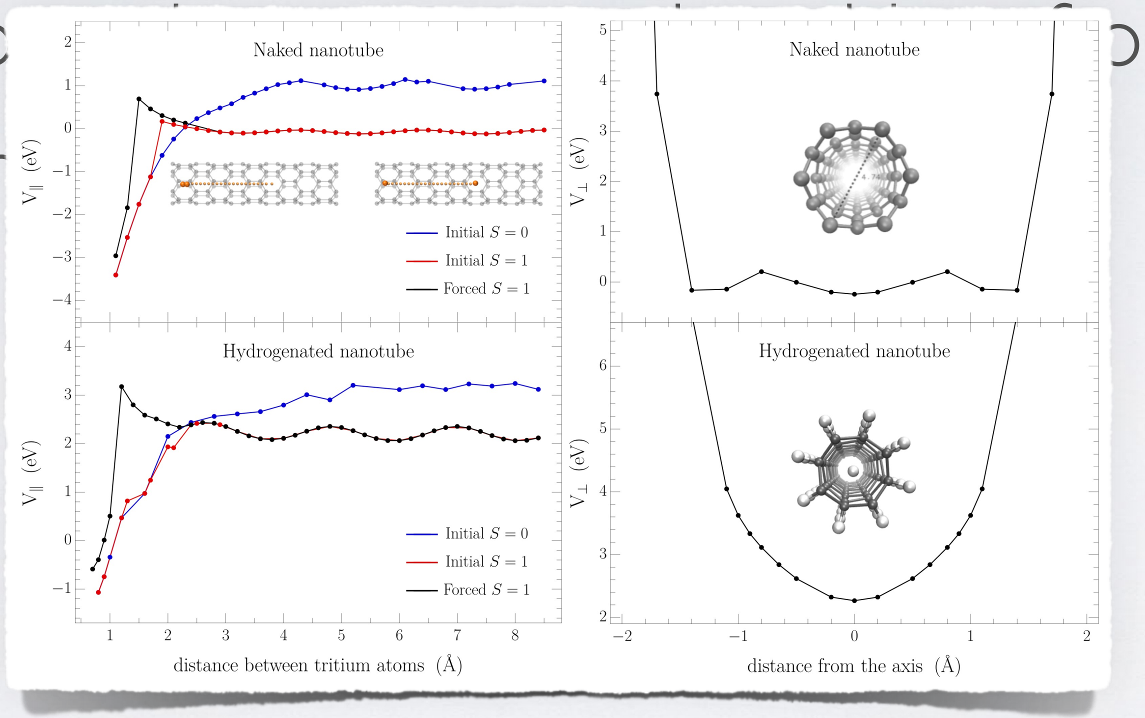


external B-field could also **prevent the formation of molecules** if two atoms are in the same nanotube

[PTOLEMY — 2203.11228]

WHY HYDROGENATED NANOTUBES?

- The reason to passivate the nanotubes with
hydro … om
stickir



[PTOLEMY — 2203.11228]

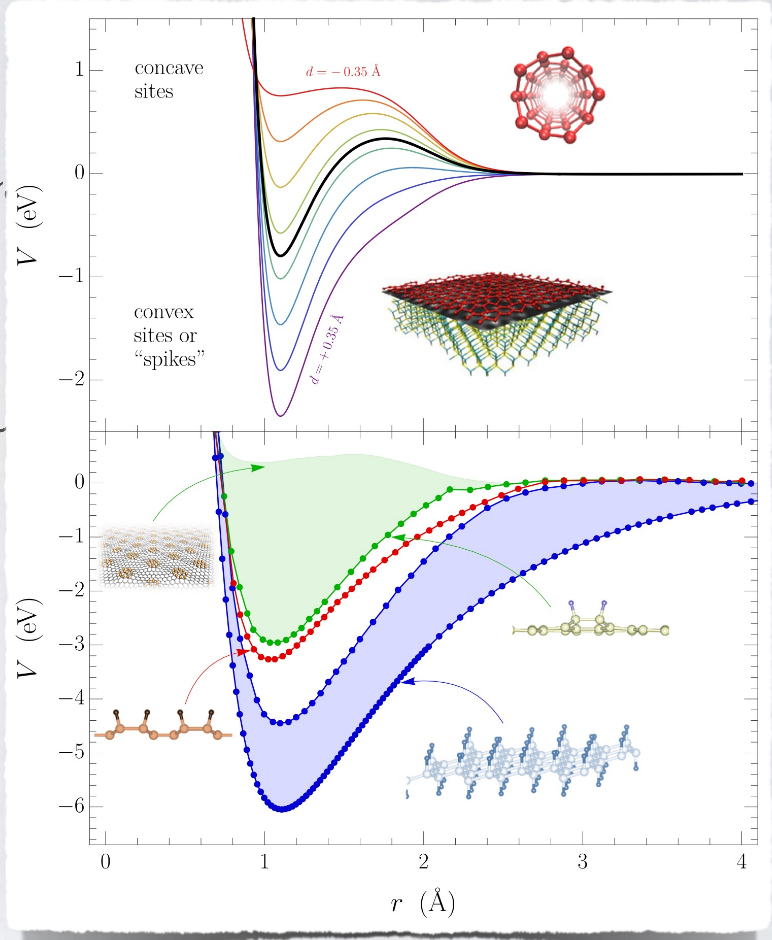
TRITIUM-GRAPHENE POTENTIAL

- The tritium-graphene potential is strongly dependent on covera
and curvature of the sheet

- For very concave sheets (nanotu
the potential is essentially not binding anymore

- The highest the coverage the deeper is the potential

[PTOLEMY — 2203.11228]



MORE DETAILS ON THE ELECTRON SPECTRUM

- Two extreme cases for the $^3He^+$ wave function (near the endpoint)
- <u>Free helium</u>:

$$\psi_{He}(\mathbf{x}) \sim e^{i\mathbf{k}_{He}\cdot\mathbf{x}} \Rightarrow \mathcal{M}_{fi} \sim \exp(-\Delta x_T^2 |\mathbf{k}_{He} + \mathbf{k}_e|^2)$$

- maximize the probability when $\mathbf{k}_{He} \simeq -\mathbf{k}_e$ probability is maximum in a region $\Delta k_{He} \sim 1/\Delta x_T$ large quantum spread
- <u>Bound helium</u>:

$$\psi_{He}(\mathbf{x}) \simeq \psi_T(\mathbf{x}) \Rightarrow \mathcal{M}_{fi} \sim \exp(-\Delta x_T^2 k_e^2) \ll 1$$

- no spread but the event is exponentially unlikely

[PTOLEMY — 2203.11228]