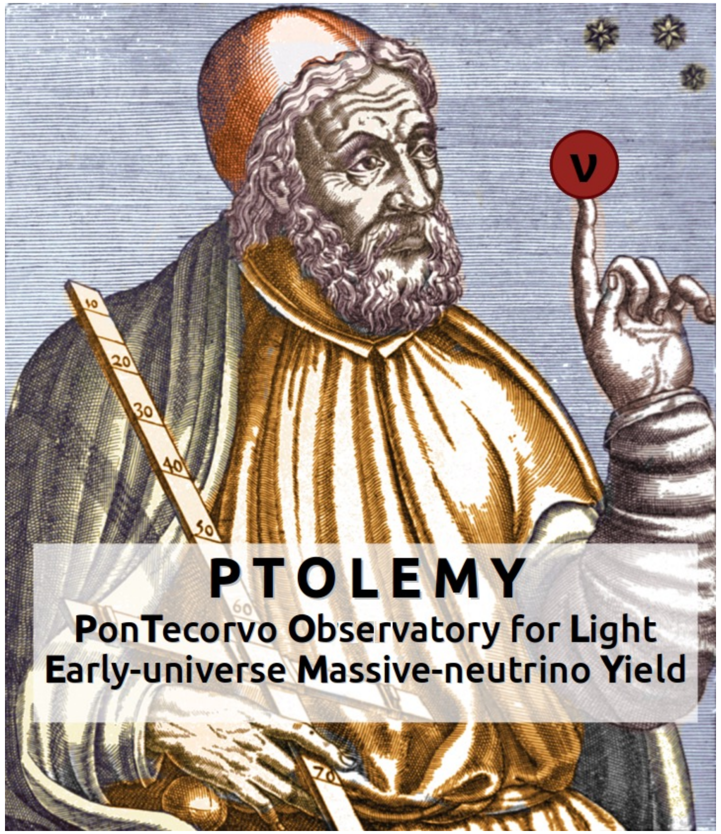
PTOLEMY: Towards a first mass measurement



https://ptolemy.lngs.infn.it

Wonyong Chung
PTOLEMY collaboration

February 2024
NuMass

PRINCETON UNIVERSITY

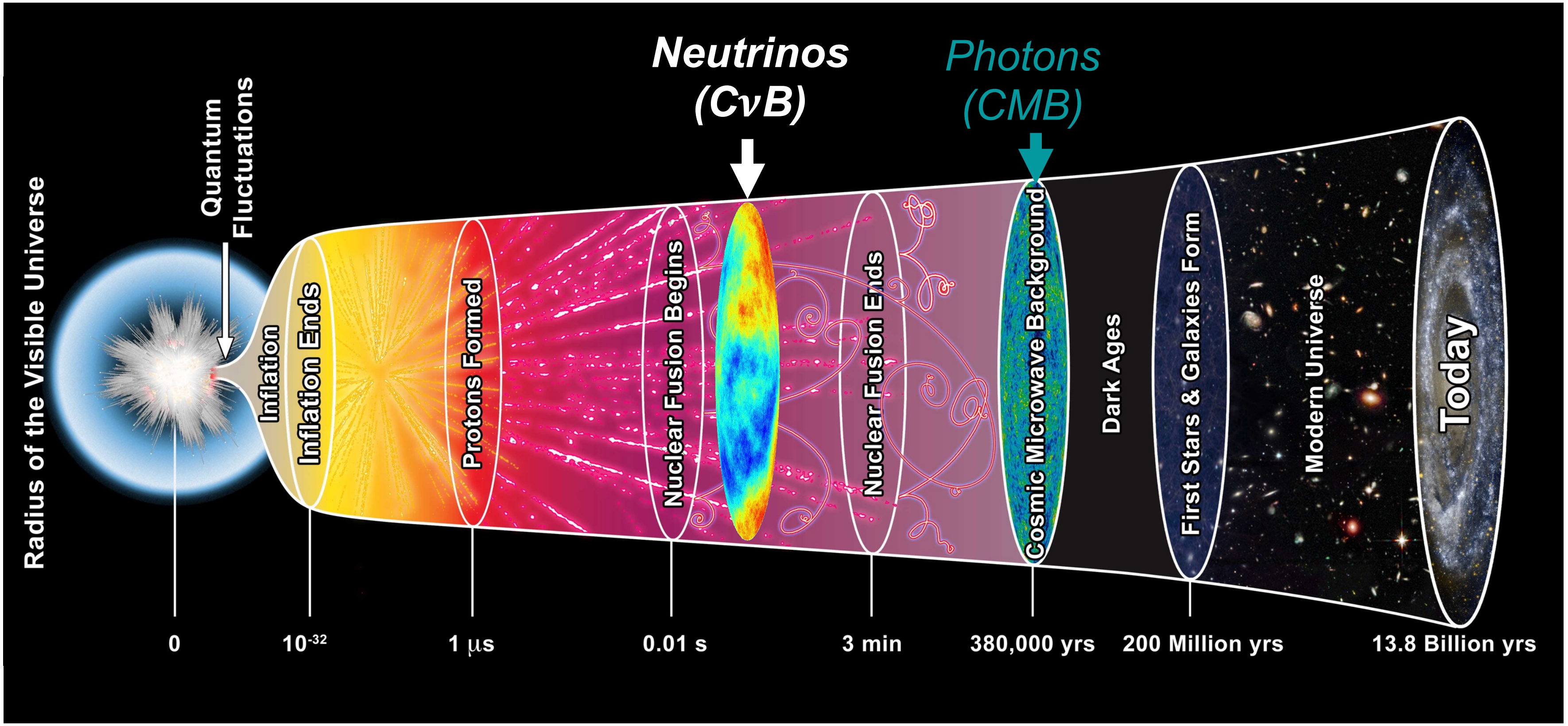
SIMONS FOUNDATION

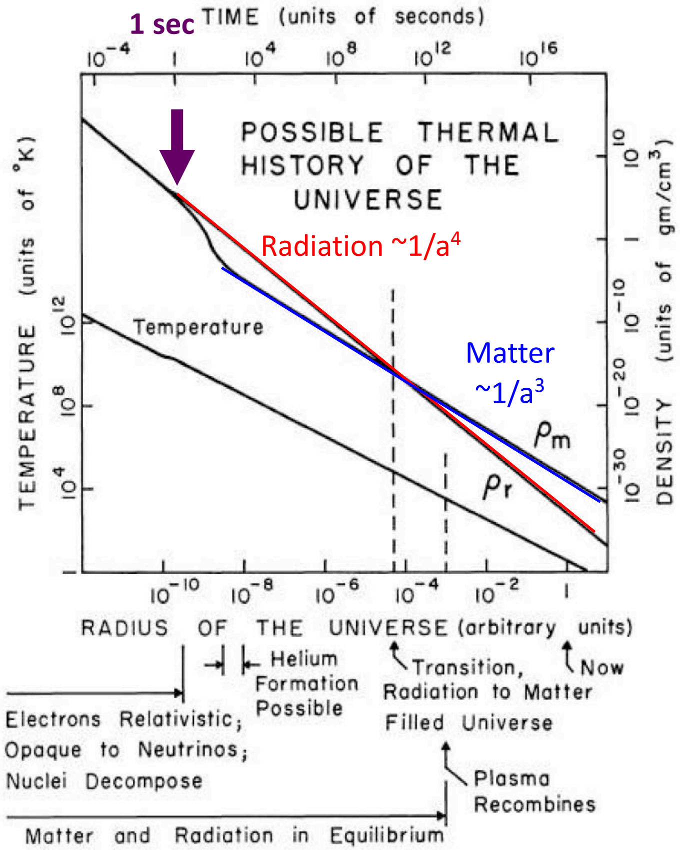
JOHN TEMPLETON FOUNDATION
Inspiring Awe & Wonder

Outline

- Cosmic Neutrino Background (CNB) and detection concept
- Physics of tritium endpoint spectrum on graphene and the neutrino mass
- PTOLEMY experimental overview and latest updates
  - Hydrogenation of monolayer graphene
  - RF antenna design and electron pitch angle
  - Transverse drift filter and slow ExB control setup
  - Microcalorimeter performance and electron sources
  - LNGS demonstrator setup
- LNGS demonstrator characterization and project timeline

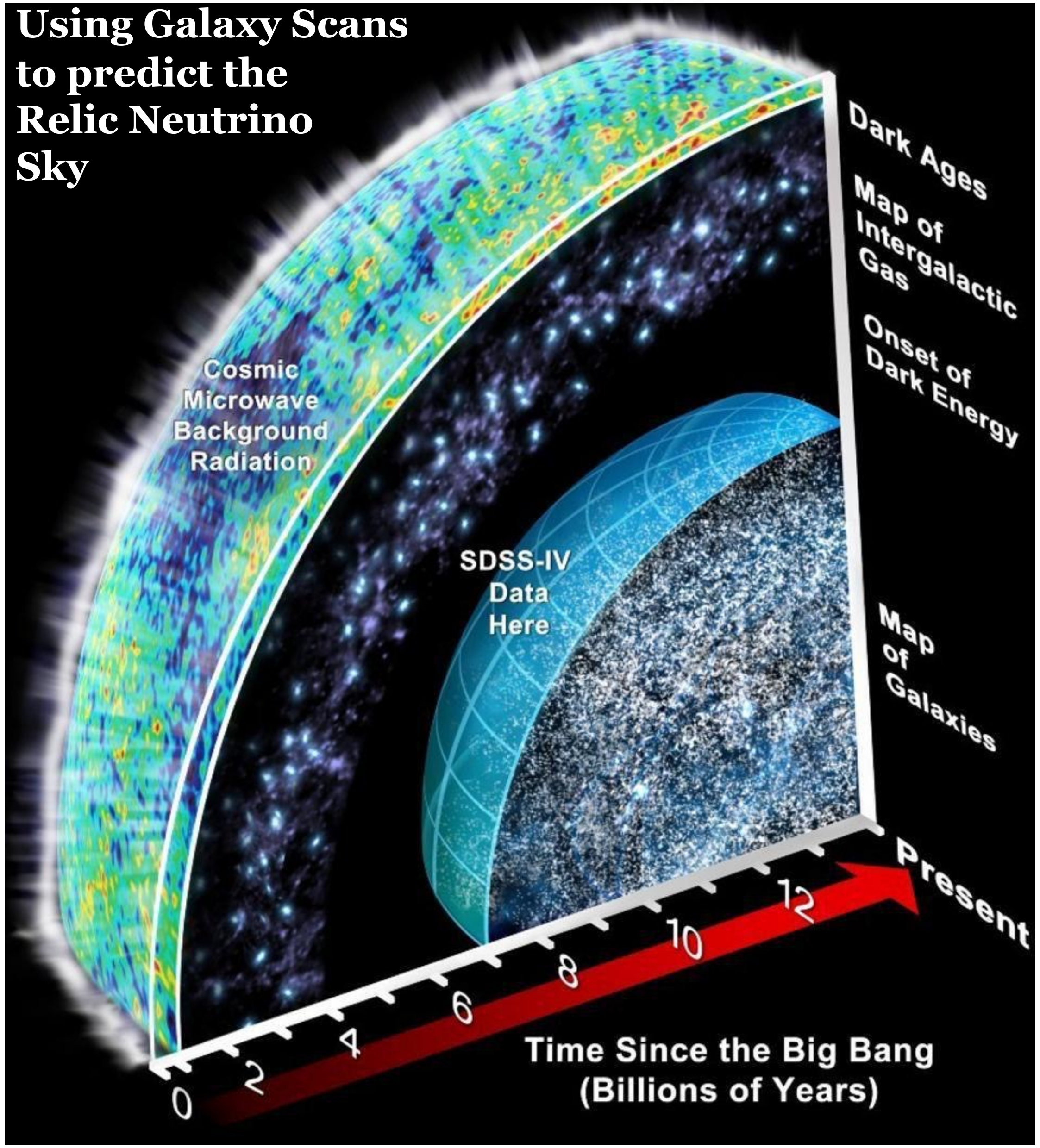
Decoupling in the early universe



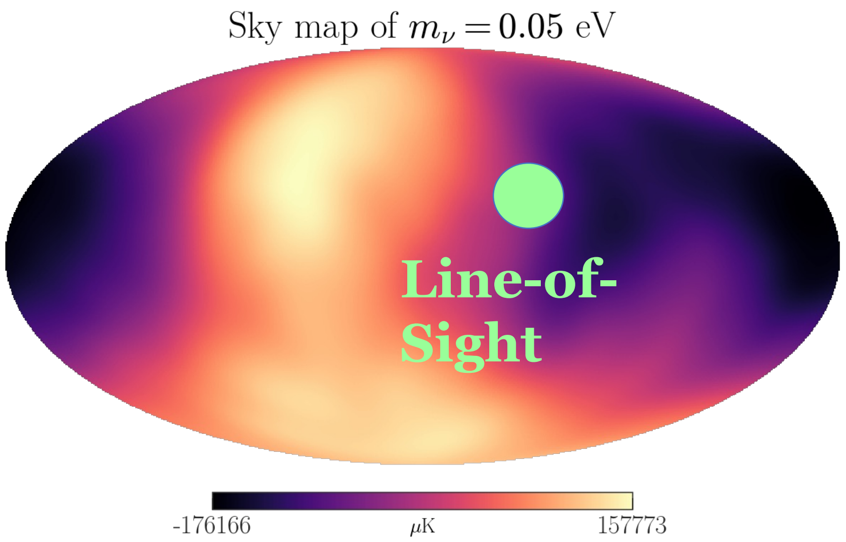


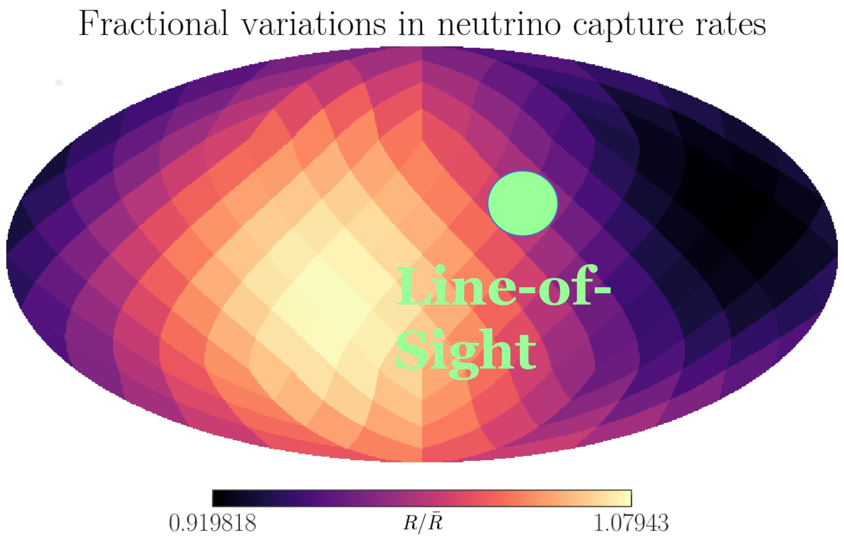
Dicke, Peebles, Roll, Wilkinson (**1965**)

Using Galaxy Scans to predict the Relic Neutrino Sky



Simulation

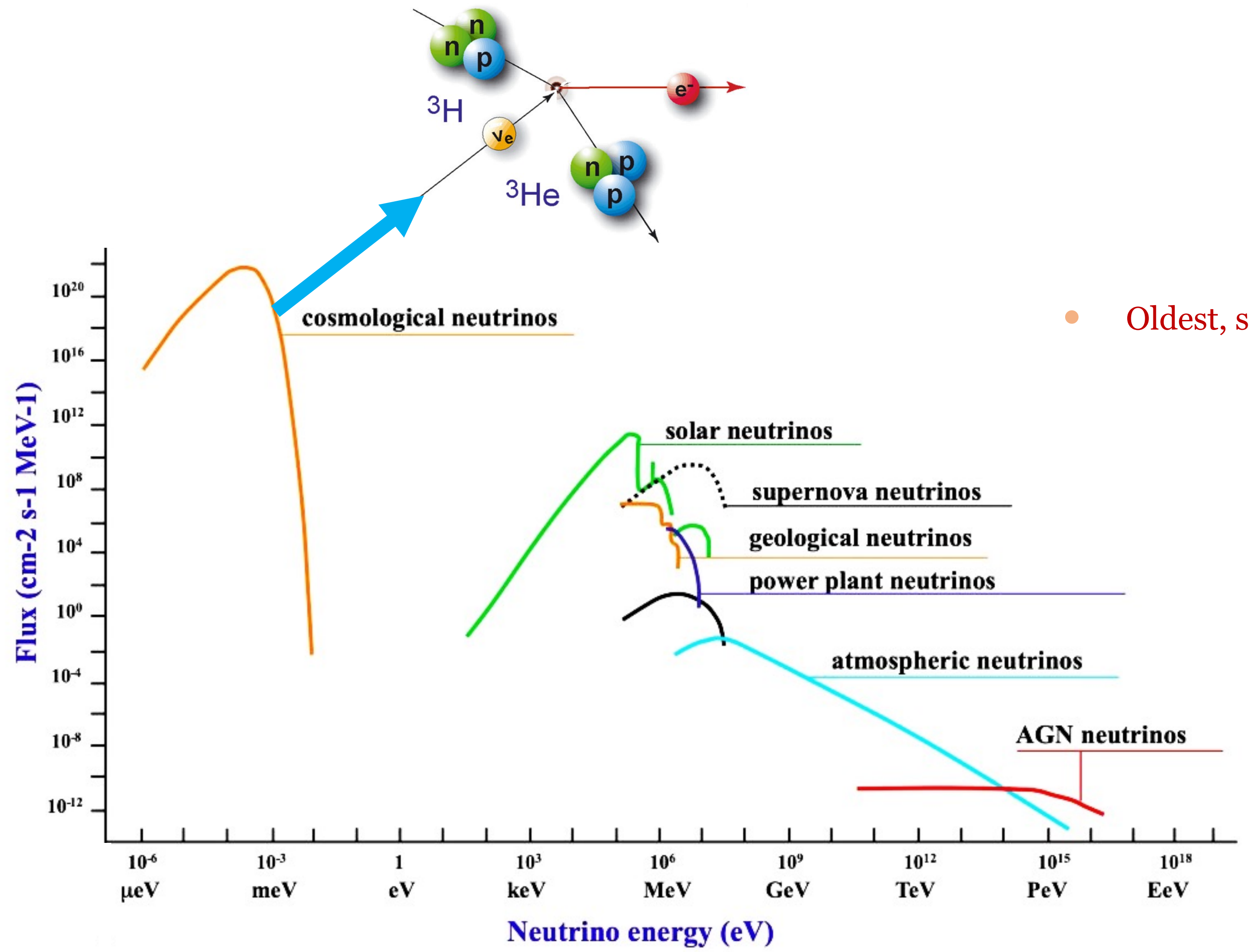




50 meV neutrino mass → CNB w/ ~10% anisotropies

G. Zhang and C. Tully [2103.01274] [2201.01888] (Highlight article: Journal cover)

Cosmic Neutrino Background



- Oldest, slowest & most abundant neutrinos in the universe

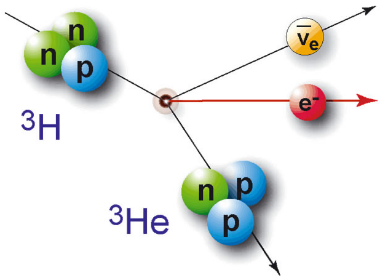
$$N_\nu = N_f \frac{3}{11} N_\gamma \Rightarrow \sim\mathbf{300/cm^3}$$

$$\langle v_{rms} \rangle \propto \frac{T}{m_\nu} > \mathbf{160\ km/s}$$

$$T_\nu(t) = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_{CMB} \Rightarrow \sim\mathbf{1.92K}$$

Detection Concept

(1962)	Basic concepts for relic neutrino detection: Steven Weinberg	[*Phys. Rev.* 128:3, 1457]
(2007)	Applied for the first time to massive neutrinos: Cocco, Mangano, Messina	[*JCAP* 06, 015]
(2021)	Revisited w.r.t. uncertainty principle: Cheipesh, Cheianov, Boyarsky	[*Phys. Rev. D* 104, 116004]

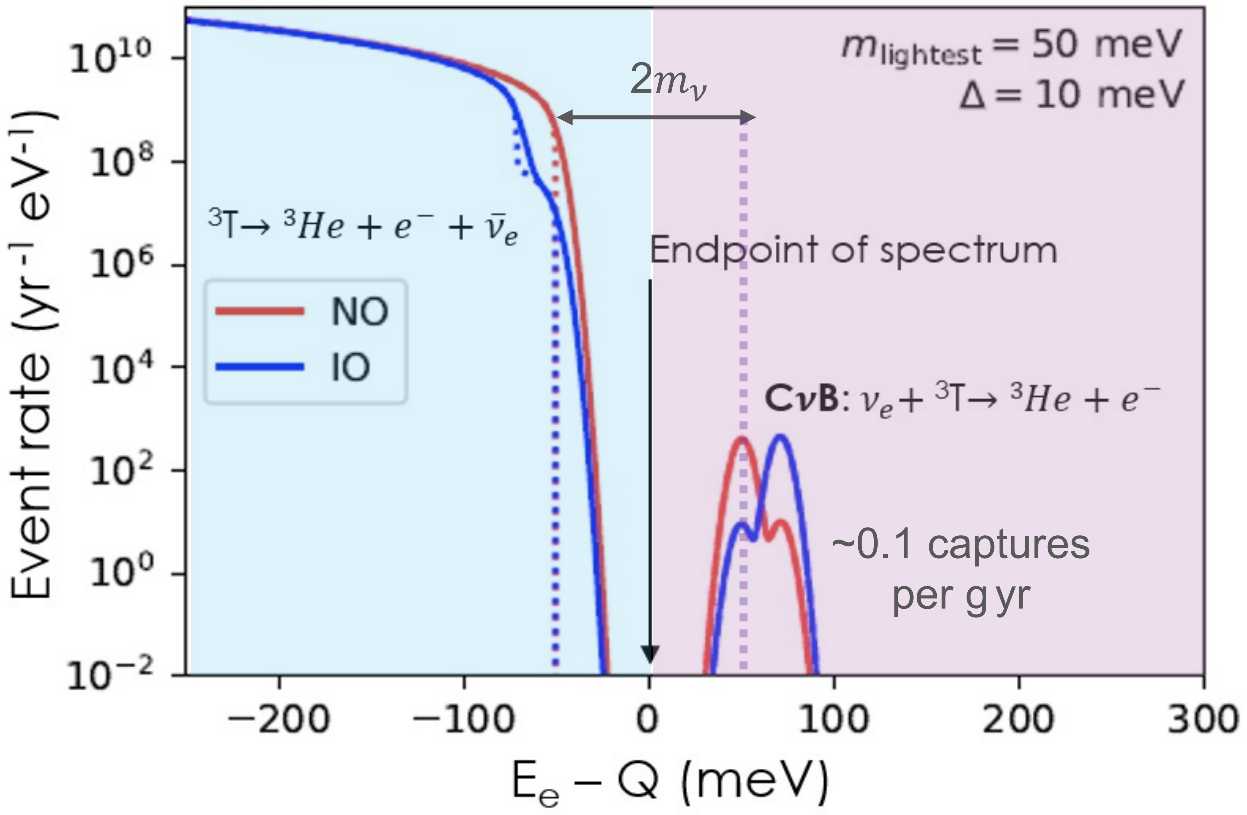


$\sigma \sim 10^{-44}$ cm²
$T_{1/2}$ = 12.32 y
E_{end} = 18.57 keV
A ~ $\mathcal{O}(10^{14})$ Bq

Neutrino momentum ~ 0.17 meV

For m_ν = 50 meV,
KE = p²/2m
= (0.17 meV)² /100 meV
= 0.3 meV

Ultra-Cold!



What do we know?

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

Electron flavor expected with
m > ~50 meV
from **neutrino oscillations**

Neutrino mass
$m_\nu < 0.8\ eV$ [KATRIN 2022]
$\sum m < 0.12\ eV$ [Planck 2018]
$m_\alpha \geq 0.05\ eV$ [Δm^2_{32} limits]

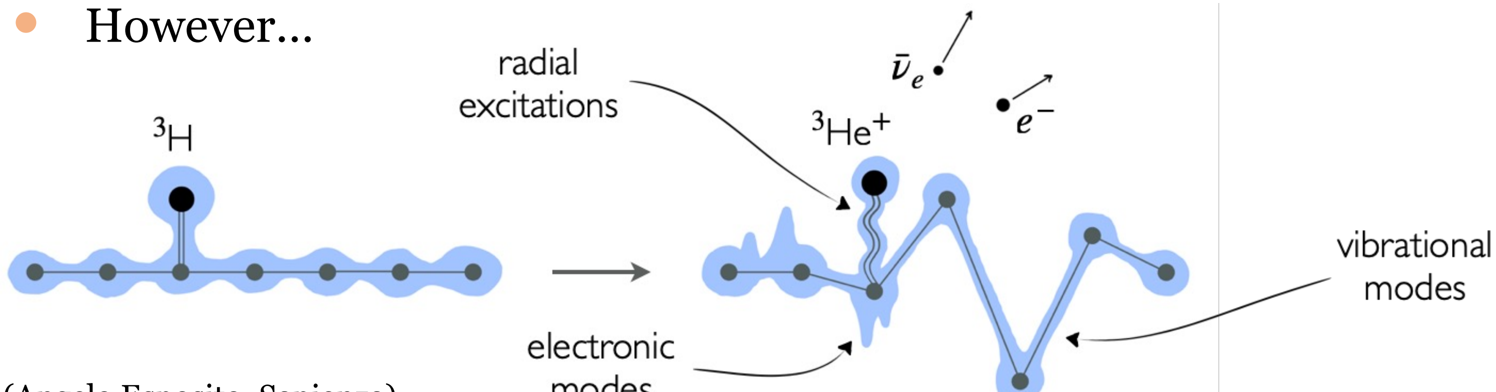
CNB Detection Requires:
few x 10⁻⁶ energy resolution set by m_ν
KATRIN ~ 10⁻⁴ (current limitation)

PTOLEMY:
10⁻⁴ x 10⁻²
(compact filter) x (microcalorimeter)

Tritium on Graphene

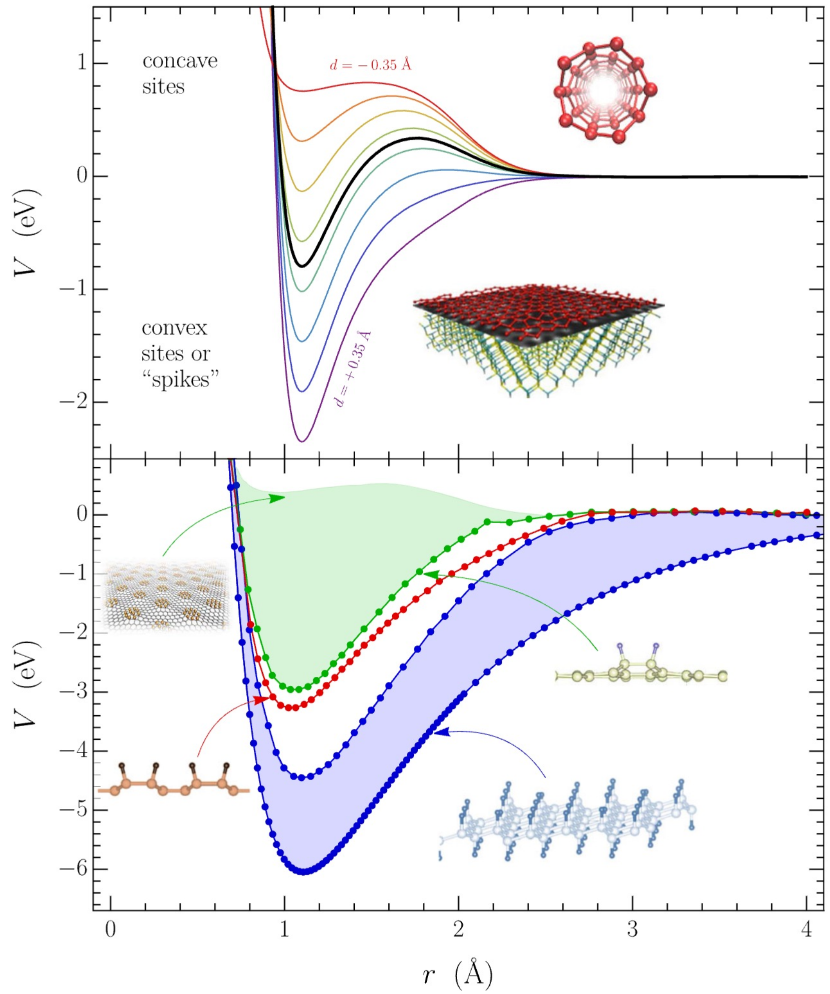
(See Angelo Esposito and Valentina Tozzini's talks)

- Initial state dictated by many-body effects
- Final state is much more crowded
  - (^{3}He$^+$ states, vibrational modes, electronic excitations, …)
- Requires precise control of theoretical uncertainties
- Uncertainty principle (~0.5 eV) makes flat graphene unsuitable for CNB detection
  - Substrates enabling delocalization under study
- However…



(Angelo Esposito, Sapienza)

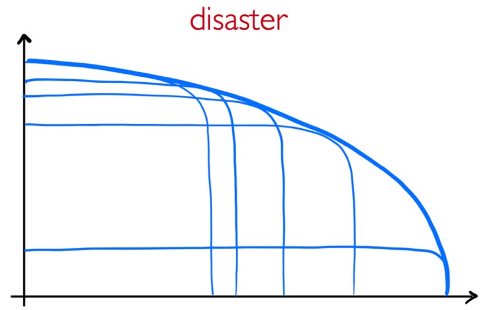
PRD 106, 053002 (2022)



Tritium on Graphene: Neutrino Mass

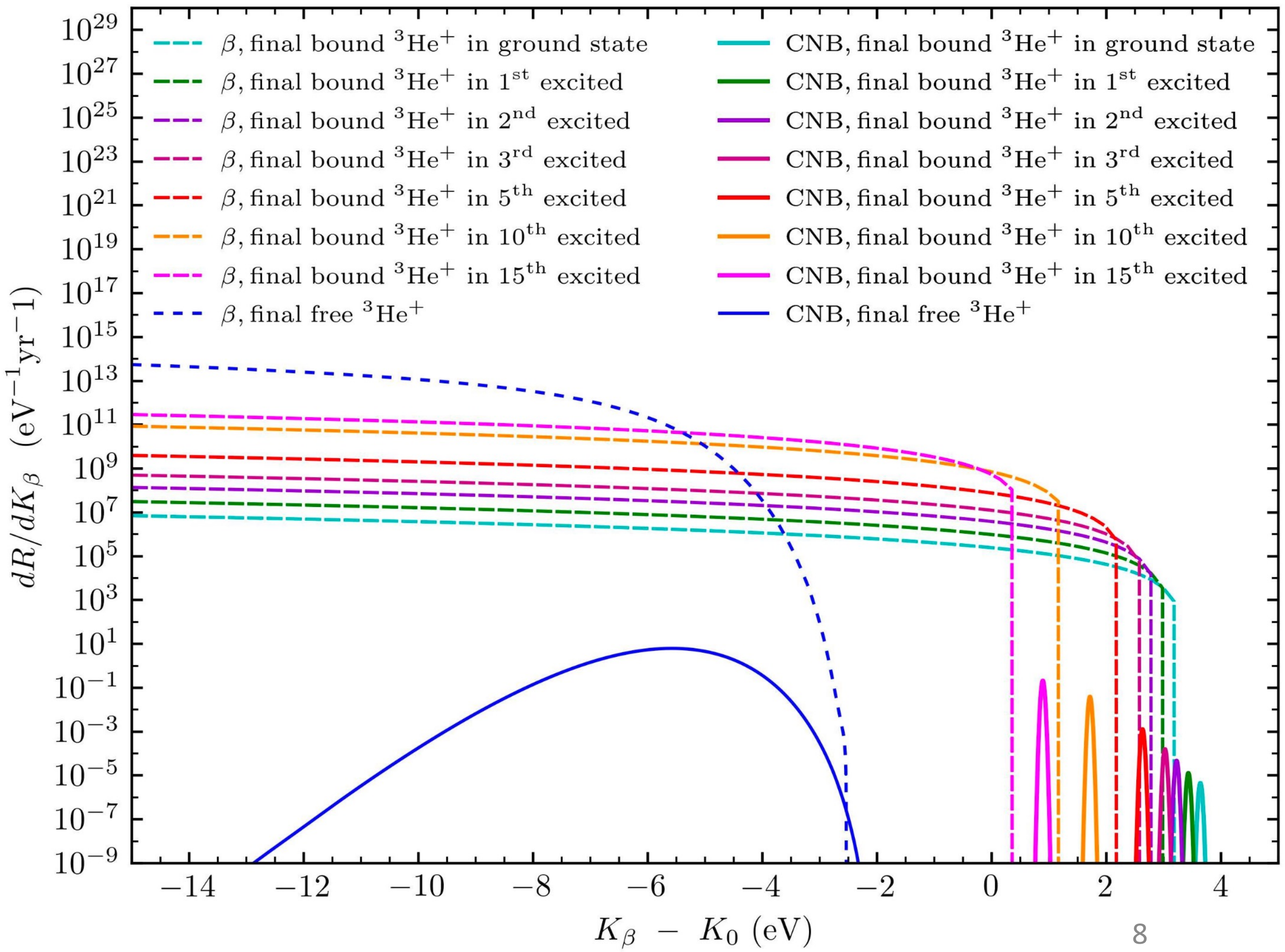
(See Angelo Esposito's talk)

- Bound ^{3}He$^+$ states at end of spectrum form a discrete step structure
- Features of steps are sensitive to m_ν
  - Size, degeneracies, slopes, …
- In principle, can fit m_ν with enough resolution O(50 meV) and statistics
- Sensitivity studies in progress



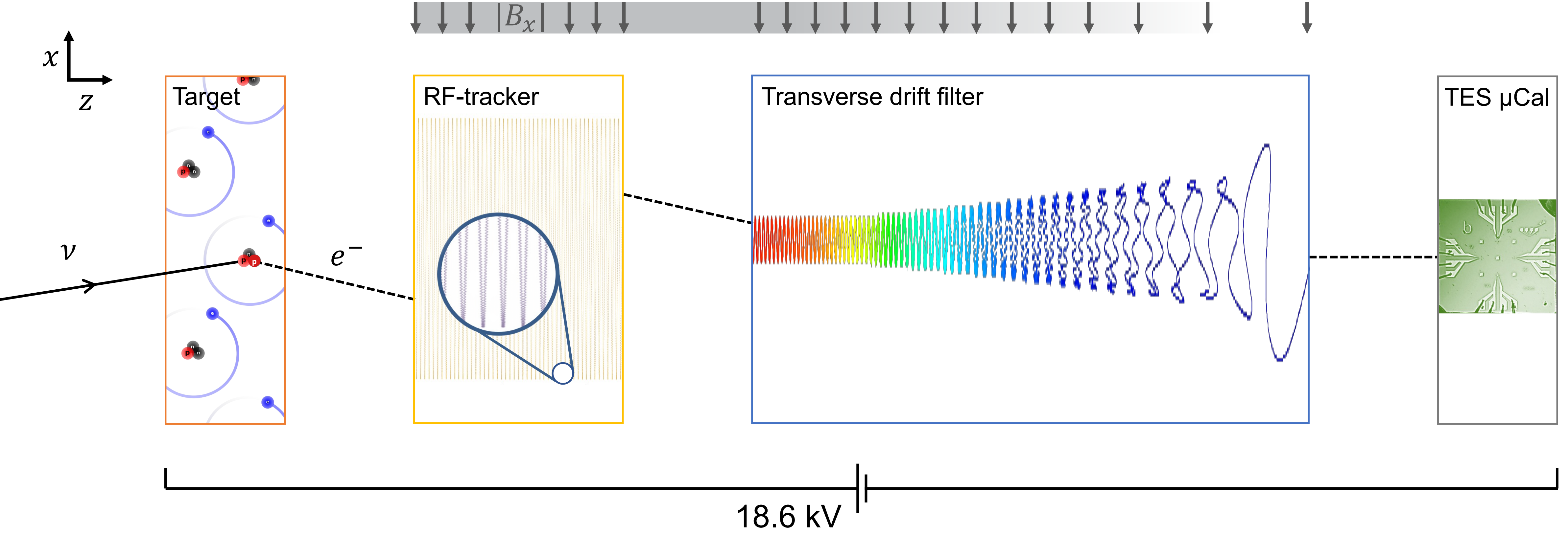
(Angelo Esposito, Sapienza)

(Andrea Casale, Sapienza)



PTOLEMY Block Diagram

$m_T \sim \mathcal{O}(100g)$ $\sigma(E_x) \sim \mathcal{O}(eV)$ $\Delta E_T \sim \mathcal{O}(100meV)$ $\sigma \sim \mathcal{O}(10\ meV)$



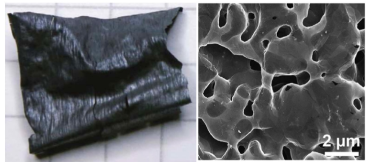
(James Mead, UvA)

$$E_{total} = q(V_{TES} - V_{target}) + E_{RF} + E_{cal}$$

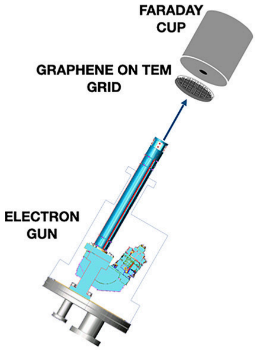
Solid state tritium target

(See Alice Apponi's talk)

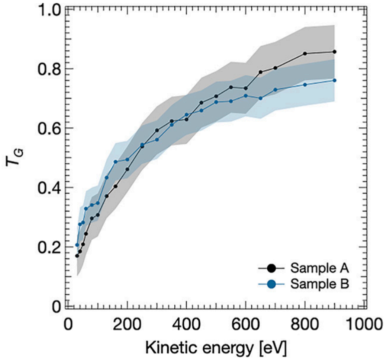
- ***Previously:***
  - ~90% hydrogenation of free-standing nanoporous graphene [Betti, M.G. et al., Nano Letters (2022)]

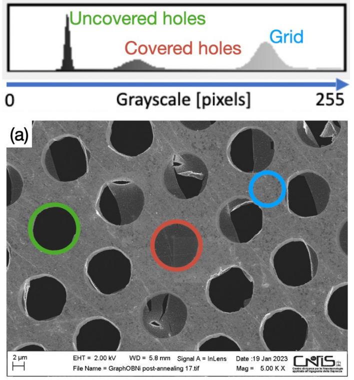


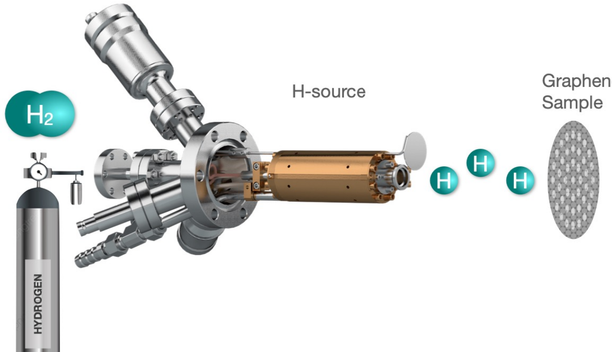
- ***Ongoing:***
  - Preparation of <u>monolayer</u> graphene
    - Clean with high temperature annealing
  - Characterization of 30-900 eV electron transmission through graphene [A. Apponi et al., Carbon (2023)]
  - Hydrogenation of monolayer graphene
    - Atomic hydrogen source – H_2 thermal cracking into H
    - ~50% saturation increase of sp^3 across samples
    - ~6.2 eV band gap consistent with 1-side hydrogenation

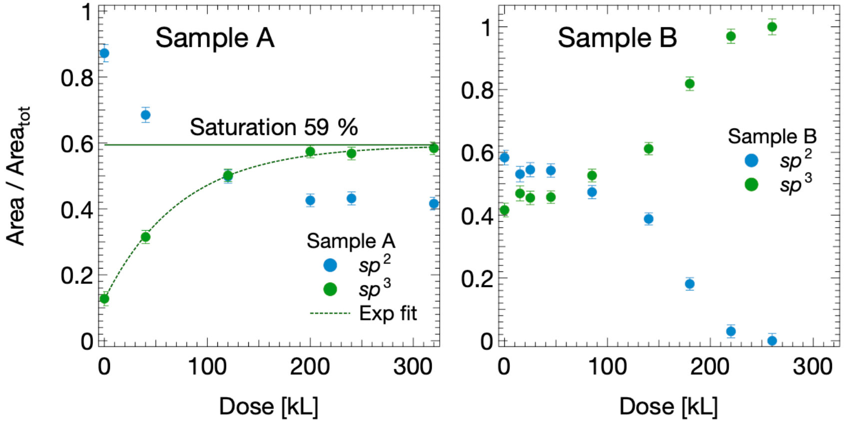


(Alice Apponi, Roma3)









RF tracking with CRES (Project 8)

(See Federico Virzi's talk)

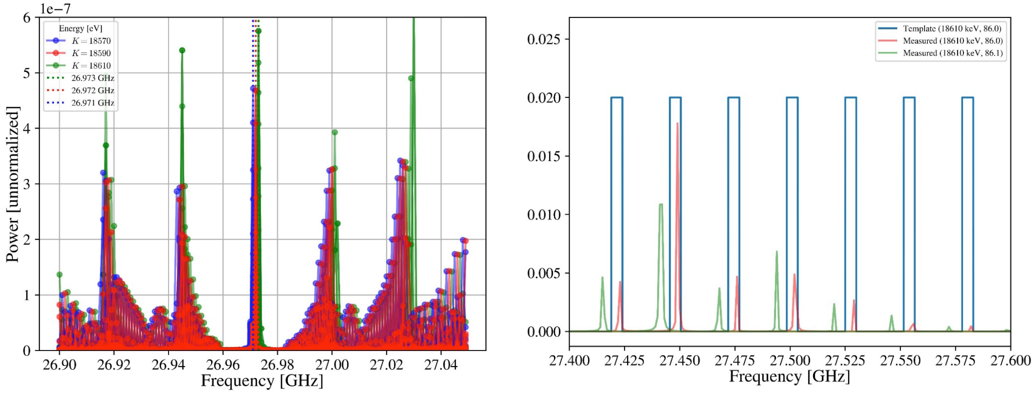
- Extract pitch angle estimate of electrons from longitudinal bouncing motion in uniform field region (~1 T)

$$K = 18.6\ keV$$

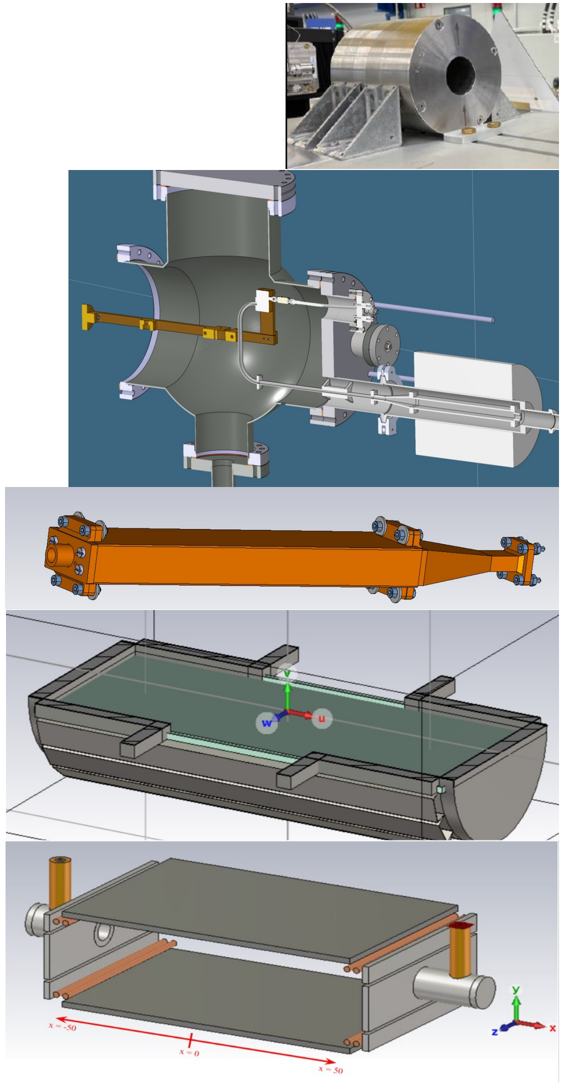
$$f_c = 27.03\ GHz$$

$$P = 1.17\ fW = 7.3\ eV/ms$$

- Test with ~1 T permanent magnet and Kr gas source at LNGS
- Antenna designs, closed-loop test at Nikhef
- Pitch-angle algorithm based on distance-matching between central peak and sidebands

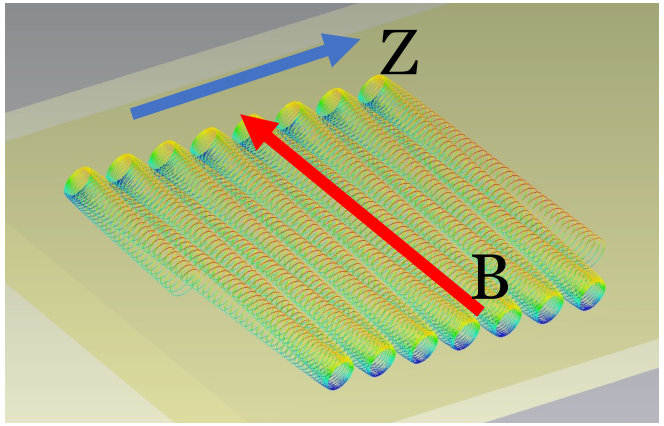


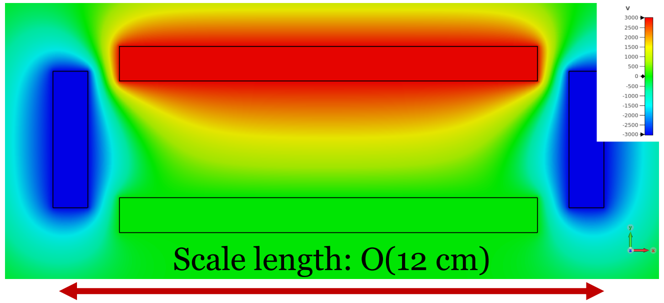
Yuno Iwasaki (Princeton)

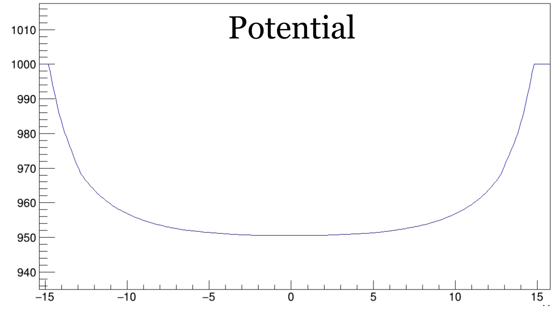


(James Mead, UvA)

(Federico Virzi, LNGS)







Electromagnetic filters: MAC-E

MAC-E filter

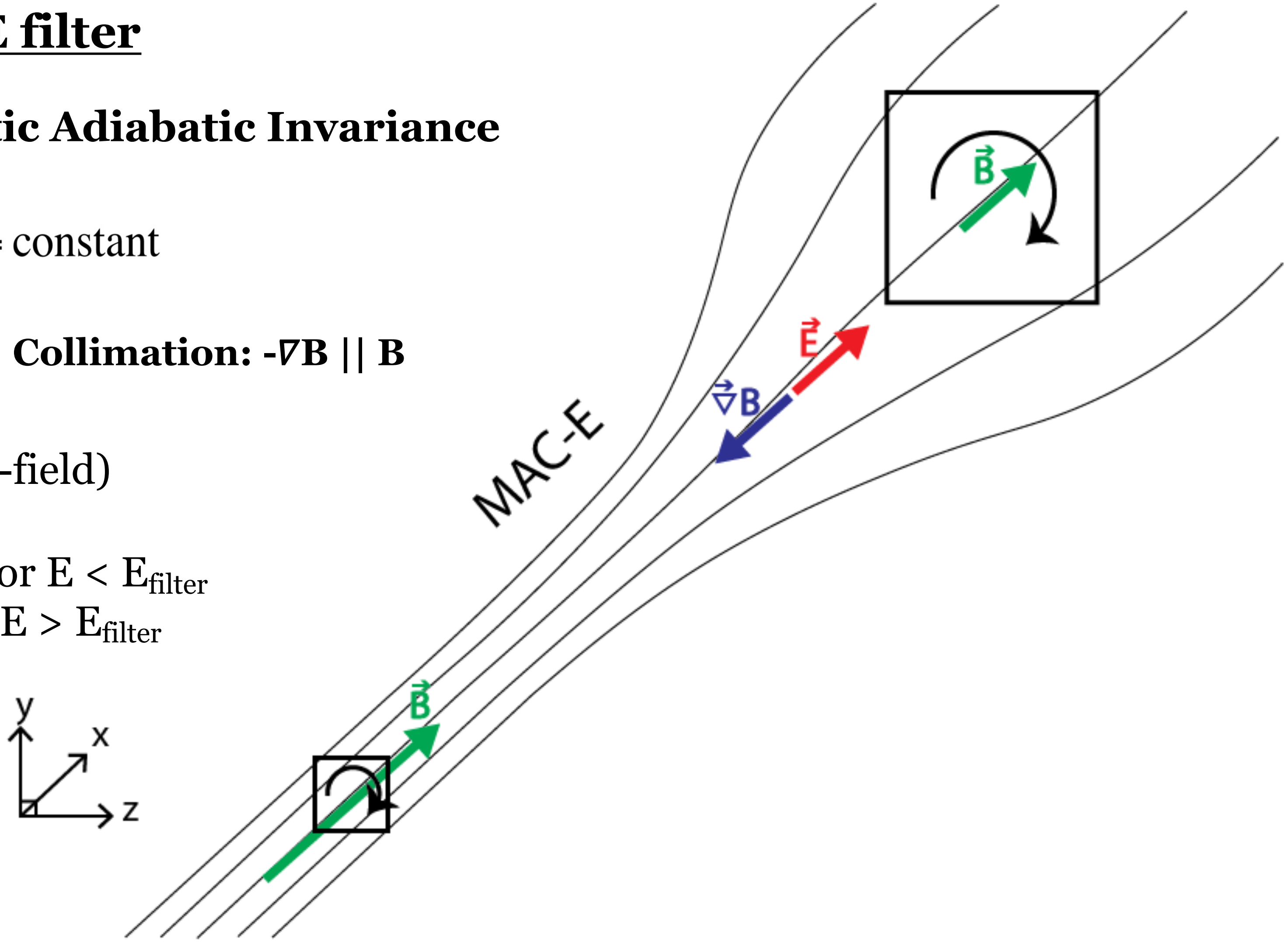
Magnetic Adiabatic Invariance

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

$p_\perp \to p_\parallel$ **Collimation: -∇B || B**

Filter (E-field)

Reflect for E < E_{filter}
Pass for E > E_{filter}



KATRIN

~1200m³

Electromagnetic filters: Transverse Drift

Transverse Drift filter

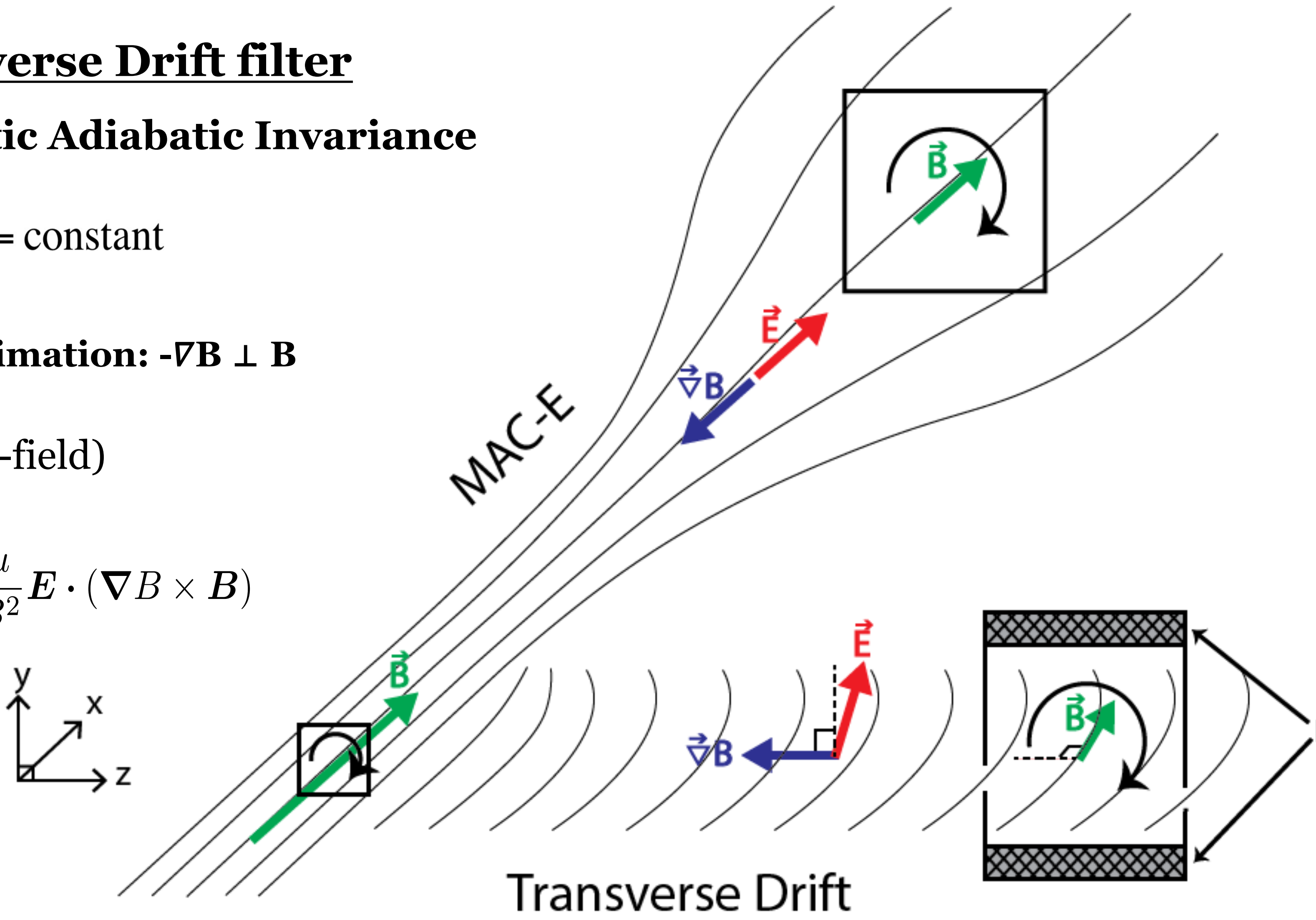
Magnetic Adiabatic Invariance

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

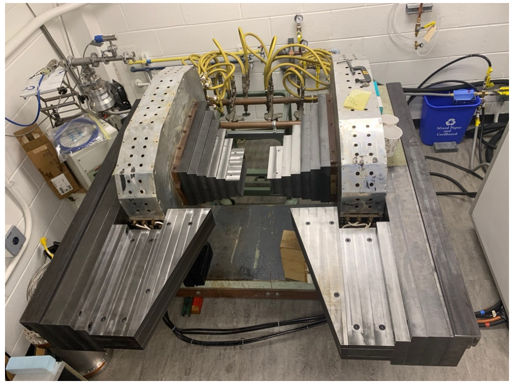
No Collimation: -∇B ⊥ B

Filter (E-field)

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



PTOLEMY



~1 m^3

Electromagnetic filters: Transverse Drift

- ExB drift acts as transport, Gradient-B drift does work to drain KE
  - Reduction of internal rotational KE of guiding-center “particle”
- Set E_z x B drift equal to Grad-B drift to produce linear trajectory transverse to B
- Potential increases along trajectory, draining transverse KE

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

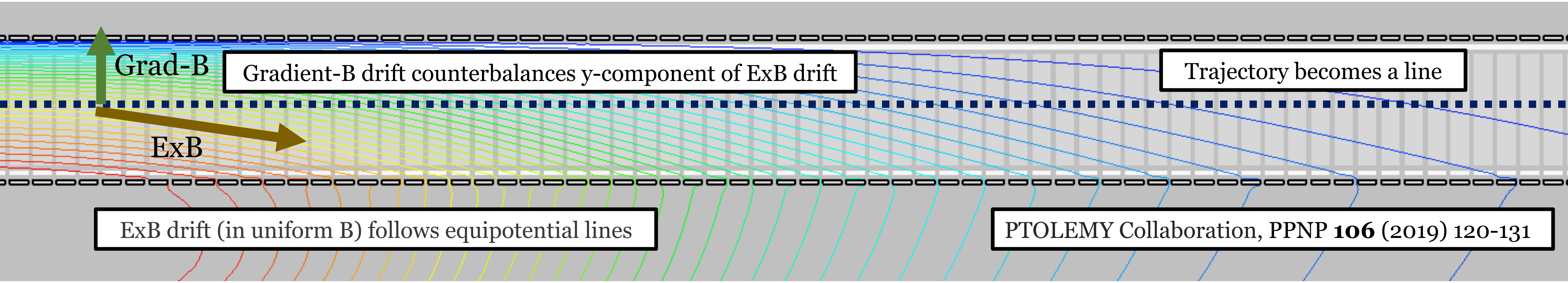
$$\boldsymbol{V}^{y}_{E\times B}(z)|_{x,y=0} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B_x^2} = \frac{E_z B_x \hat{\boldsymbol{y}}}{B_x^2} = \frac{E_z}{B_x}\hat{\boldsymbol{y}}$$

$$\frac{E_z}{B} = \frac{\mu}{q\lambda} = -\frac{\mu}{qB}\frac{\partial B_x}{\partial z}$$

For pitch 90:

$$B_x = B_0 \cos\left(\frac{x}{\lambda}\right) e^{-z/\lambda}\,,$$
$$B_y = 0\,,$$
$$B_z = -B_0 \sin\left(\frac{x}{\lambda}\right) e^{-z/\lambda}$$

$$E_x = 0\,,$$
$$E_y = E_0 \cos\left(\frac{y}{\lambda}\right) e^{-z/\lambda}\,,$$
$$E_z = -E_0 \sin\left(\frac{y}{\lambda}\right) e^{-z/\lambda}$$



Gradient-B drift counterbalances y-component of ExB drift

Trajectory becomes a line

ExB drift (in uniform B) follows equipotential lines

PTOLEMY Collaboration, PPNP **106** (2019) 120-131

Electromagnetic filters: Transverse Drift

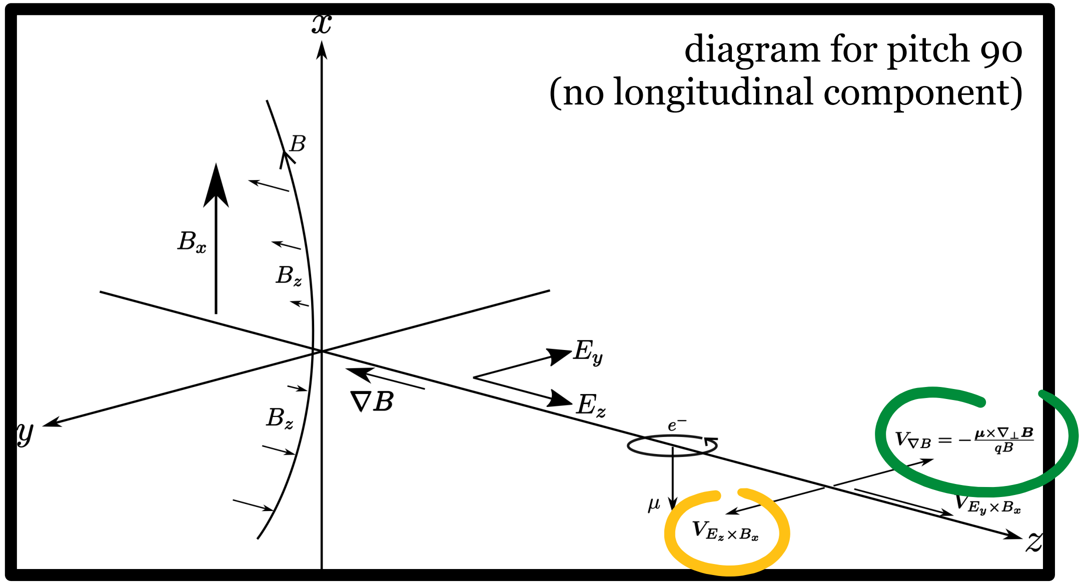
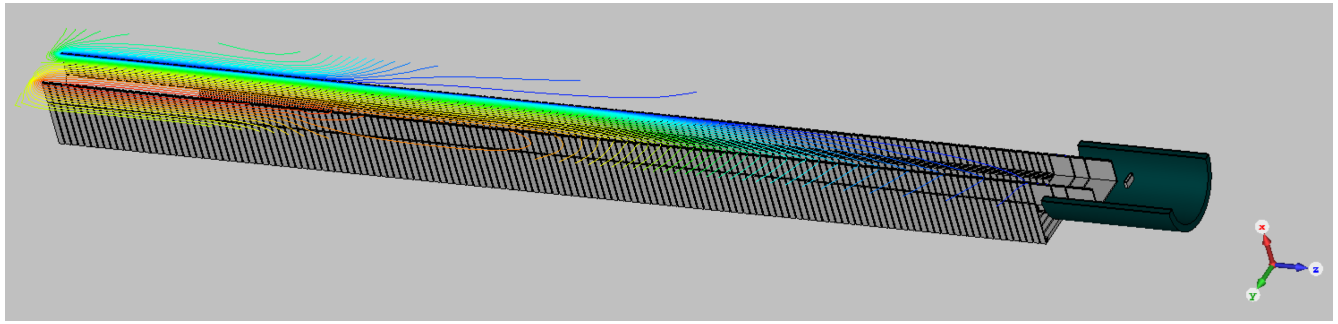
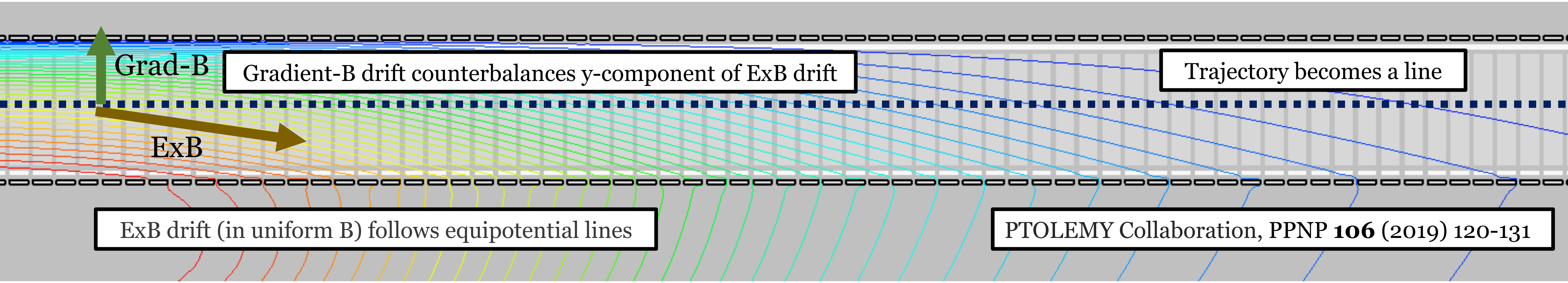


diagram for pitch 90
(no longitudinal component)





Gradient-B drift counterbalances y-component of ExB drift

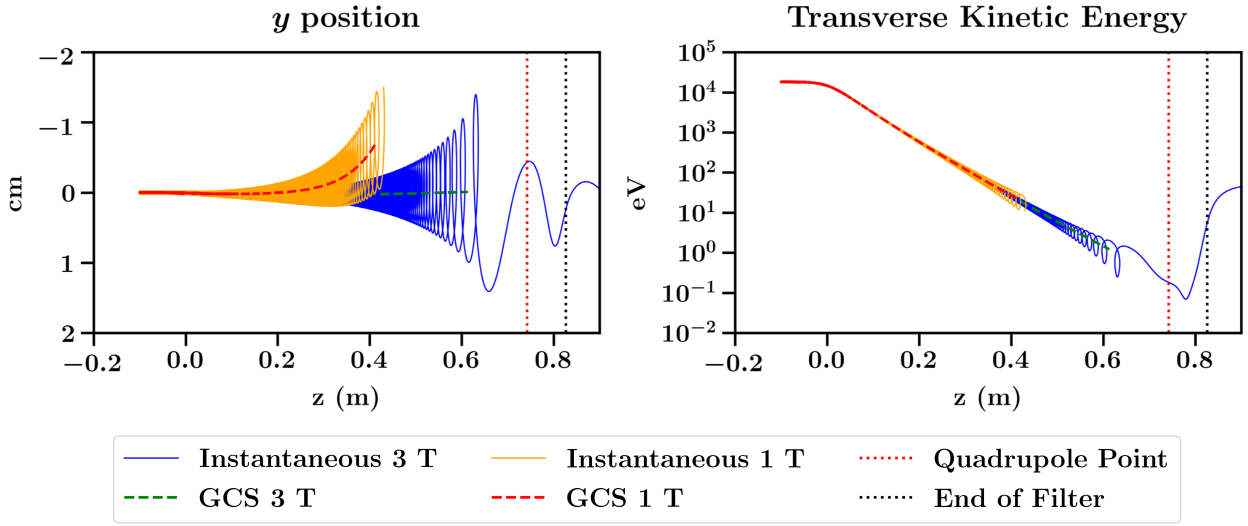
Trajectory becomes a line

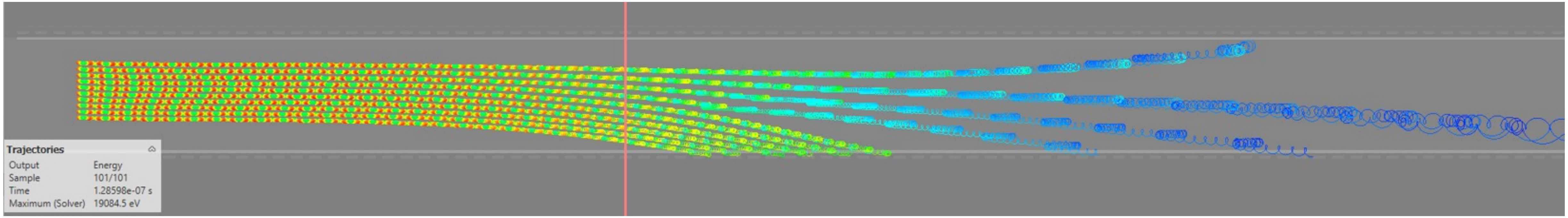
ExB drift (in uniform B) follows equipotential lines

PTOLEMY Collaboration, PPNP **106** (2019) 120-131

Transverse drift filter performance: energy selector

- Exponential rate of energy drain
- Drifts not balanced for particles with incorrect transverse KE (pitch)
- Perf. 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)





Output	Energy
Sample	101/101
Time	1.28598e-07 s
Maximum (Solver)	19084.5 eV

PTOLEMY Collaboration, JINST 17 (2022) P05021

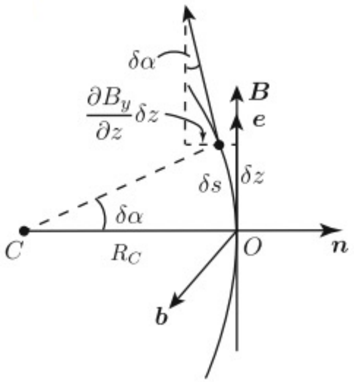
Transverse Drift Filter: Magnet Design

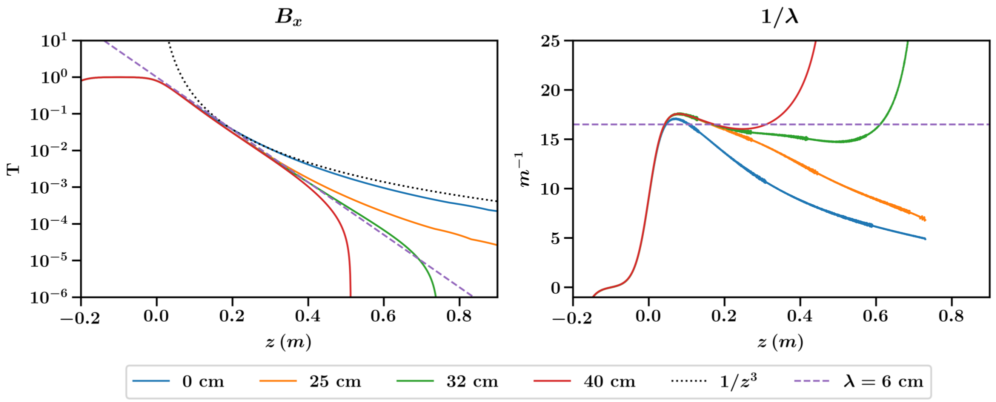
- “Let the geometry do the work for you”
  - Magnetic flux recycled through iron extensions to constrain growth of field line radius
- Exponential decay parameter λ is equal to radius of curvature of field lines

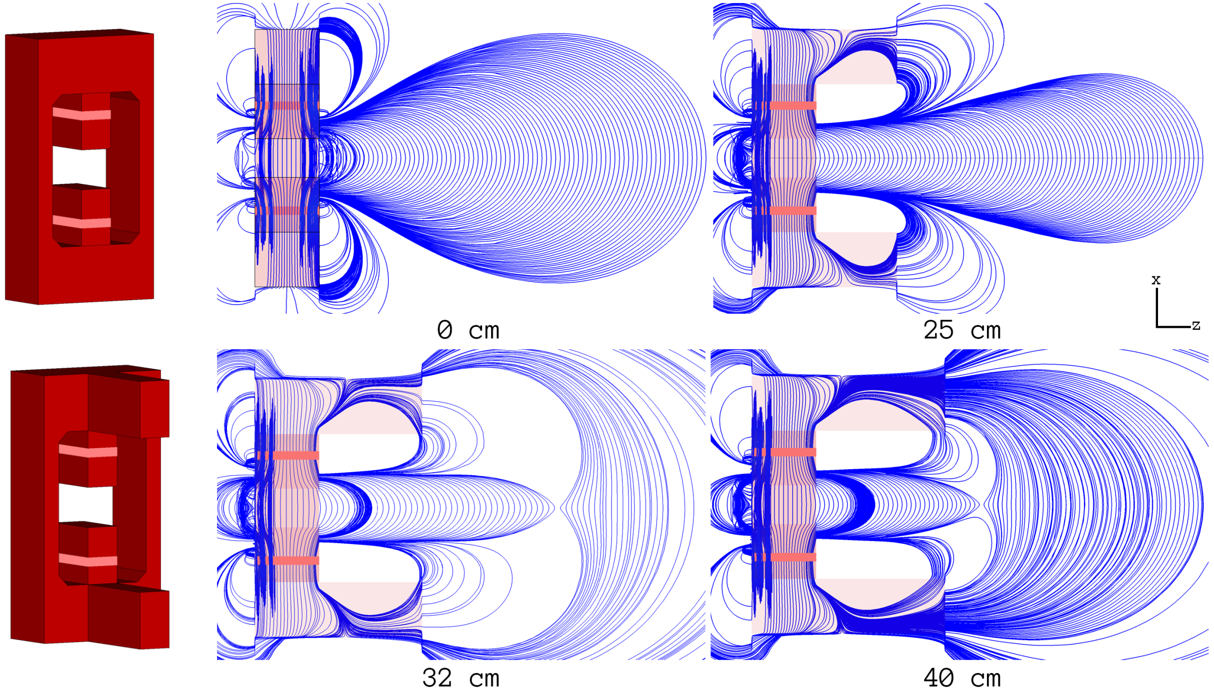
$$\frac{\partial B_y}{\partial z} = -\frac{B}{R_c} \qquad \nabla_\perp B = -\frac{B}{R_c}\hat{\boldsymbol{n}}$$

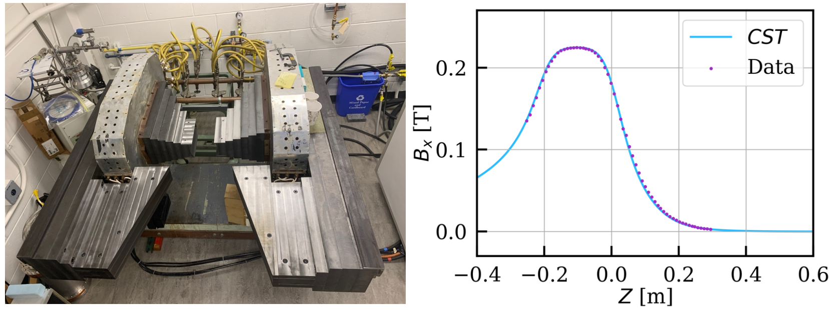
$$\frac{\partial \boldsymbol{e}}{\partial s} = -\frac{\boldsymbol{n}}{R_c} \quad \text{(by definition of curvature)}$$

- First realized experimentally at Princeton, scaled up design for LNGS demonstrator









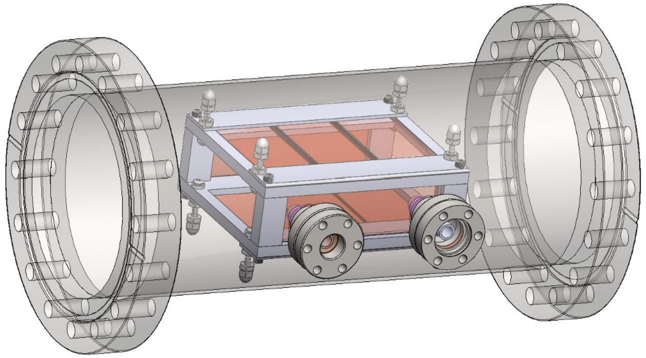
(Andi Tan, Princeton)

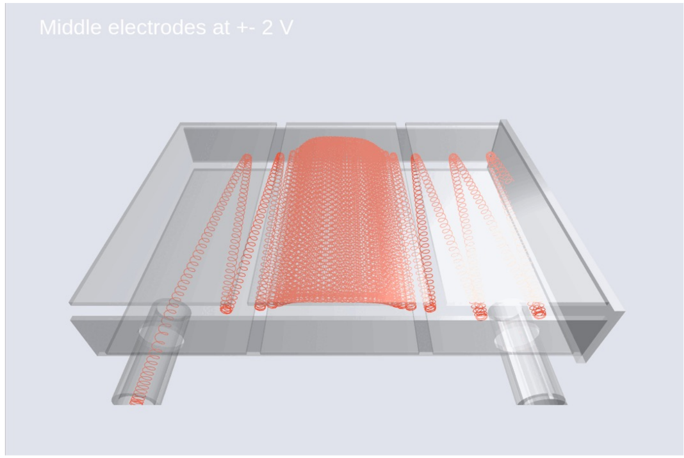
PTOLEMY Collaboration, JINST 17 (2022) P05021

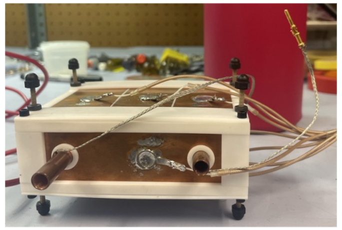
Princeton slow drift and filter setup

- Demonstrate ExB drift control
  - C-14 source and APD readout

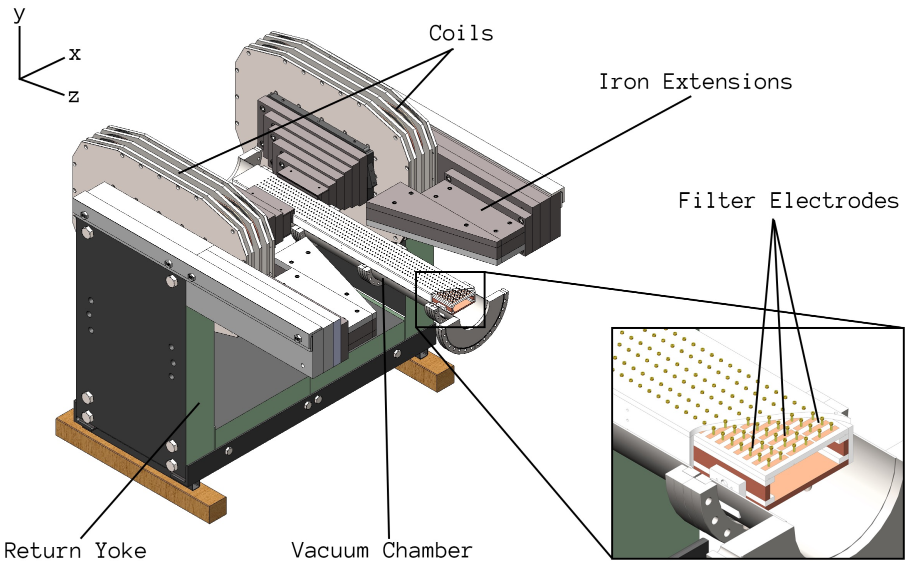
- Proof-of-concept filter (and in reverse, injection) aiming for ~2 order of magnitude reduction in KE



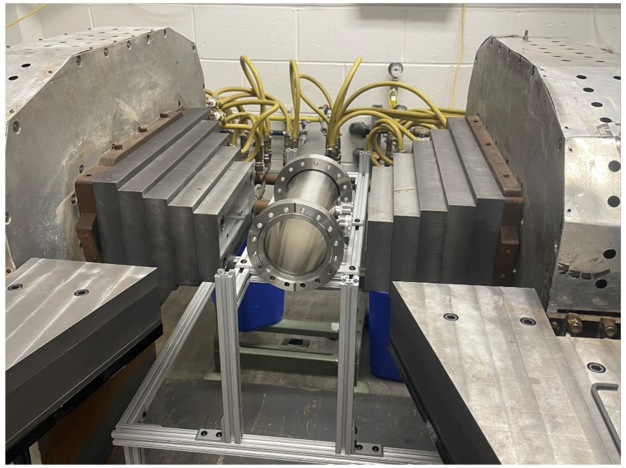


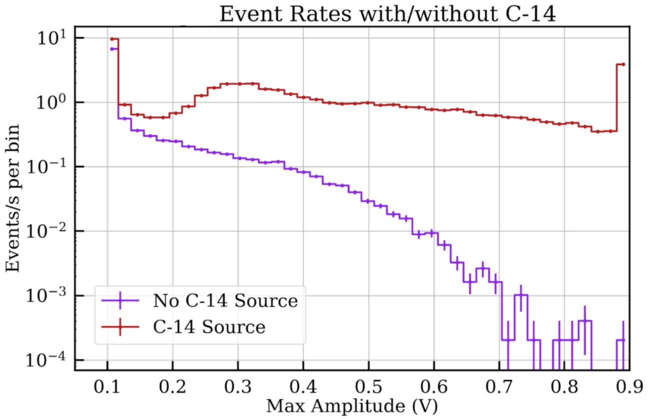


(Andi Tan, Princeton)



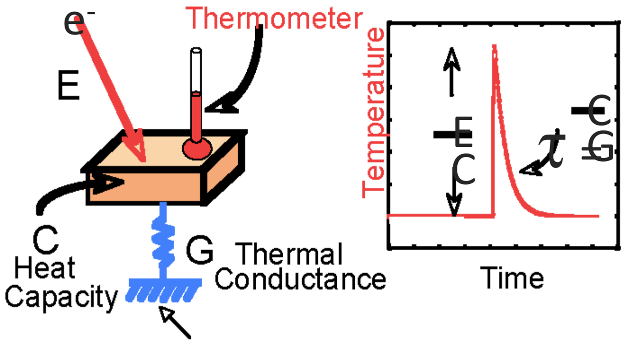
(Mark Farino, Princeton)



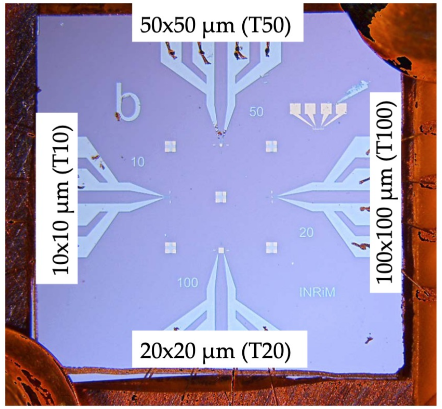


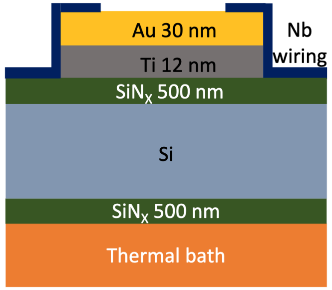
Measurement: Microcalorimeter

- Goal for electron resolution: $\Delta E_e = 0.05$ eV @ 10 eV
- First characterizations done with optical photons
  - Latest reported: $\Delta E = 0.114$ eV @ $\lambda = 1540$ nm (0.8 eV)
- Continued work to improve energy resolution
  - T_c – material, bilayer (proximity effect), annealing
  - C – material, volume (area & thickness), T_c
  - α - deposition, edges, wiring material
- Electron source work in progress: photoemission and field emission



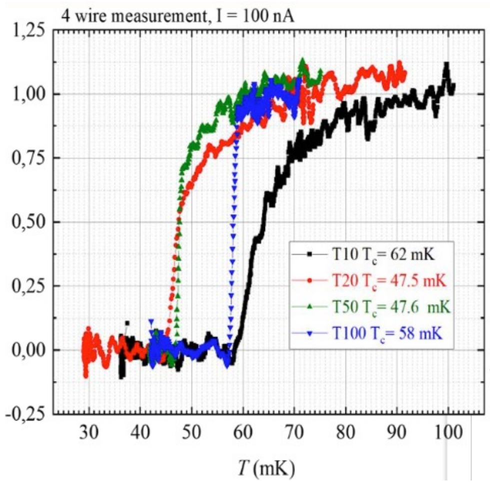
~ 100 mK cold bath (refrigerator)

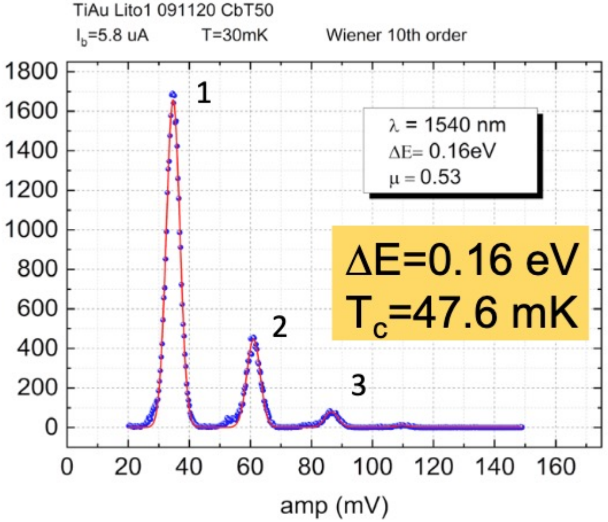


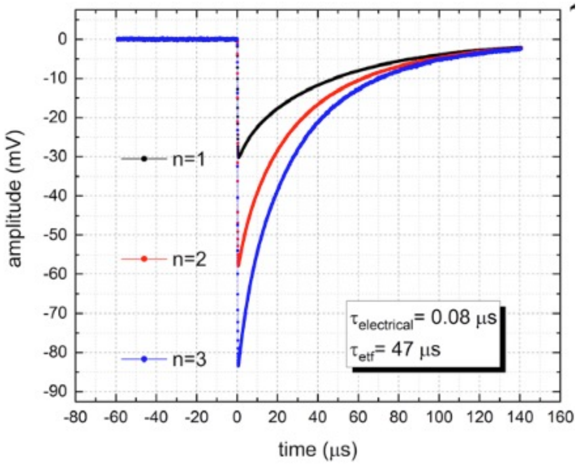


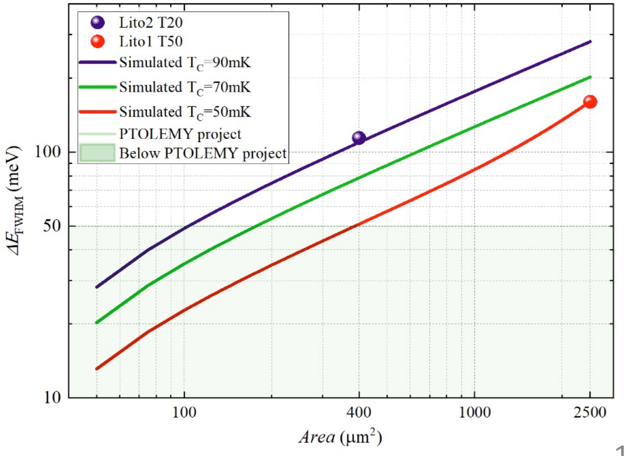
J. Low Temp. Phys. 199 (2020) 138-142

(Mauro Rajteri, Carlo Pepe, INRiM)









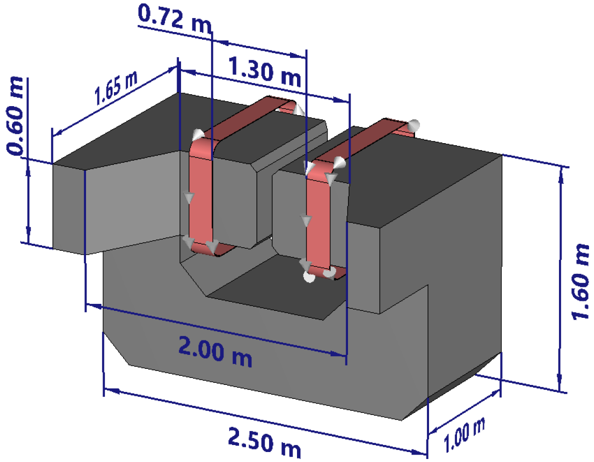
LNGS demonstrator setup

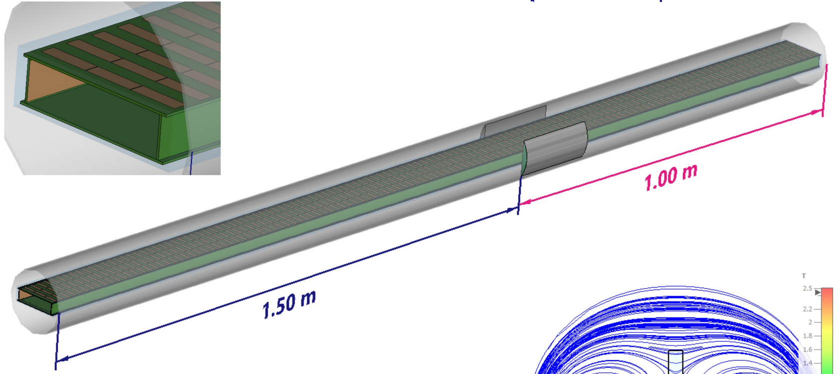
- Magnet under commisssion for delivery by EOY 2024
  - Field parameters show good agreement with simulation, meets requirements for transverse drift filter

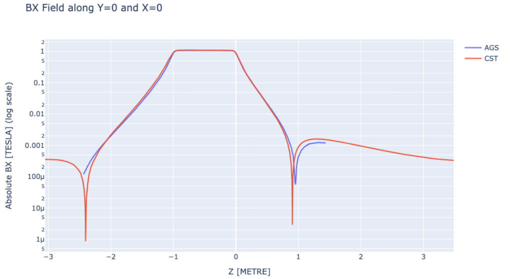
- ~2.5 m long electric field cage for target injection, RF, filter

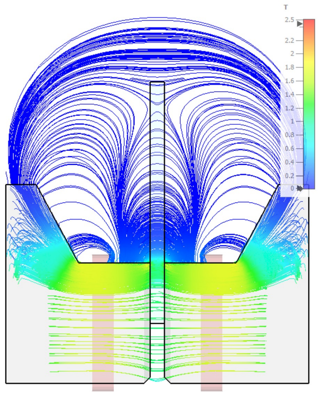
- Permanent magnet based target injection
  - Uses principles of MAC-E filtering to reject low pitch electrons
  - Enables large pitch angle cuts
  - *See also Federico Virzi's talk*

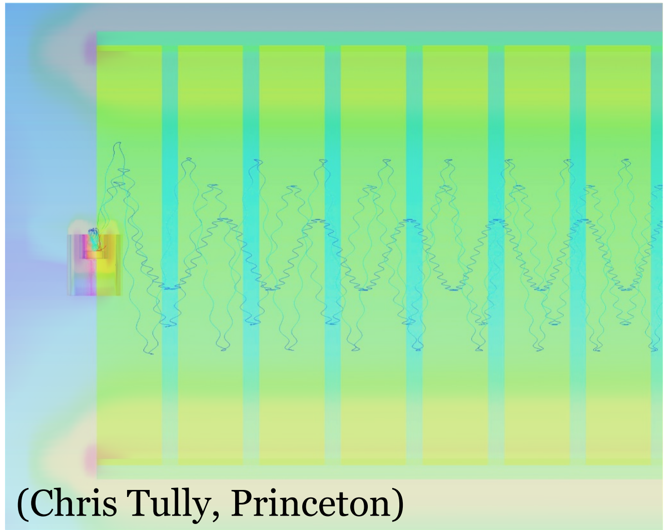
(Andi Tan, Princeton)



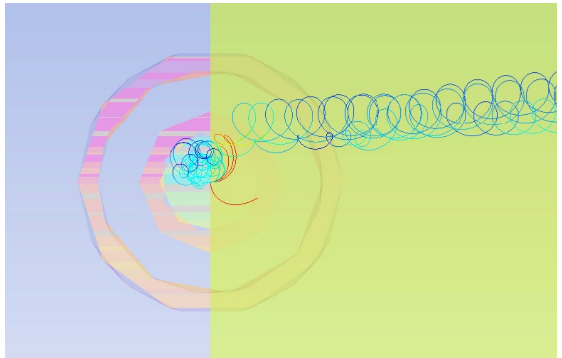






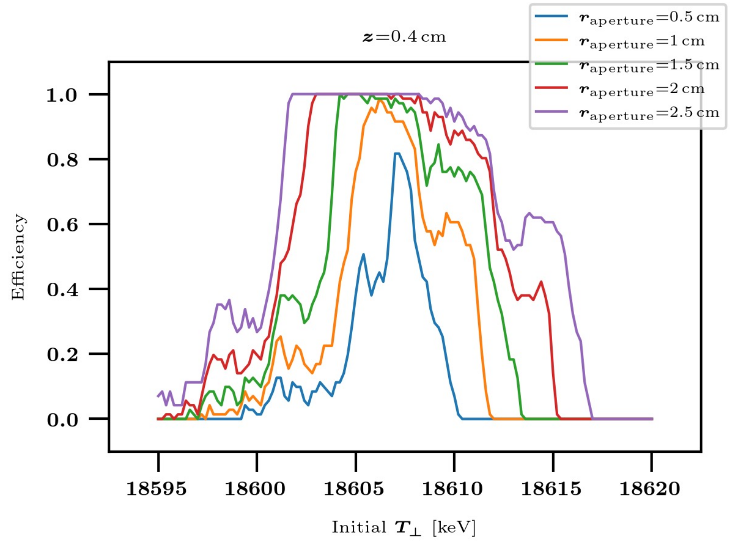


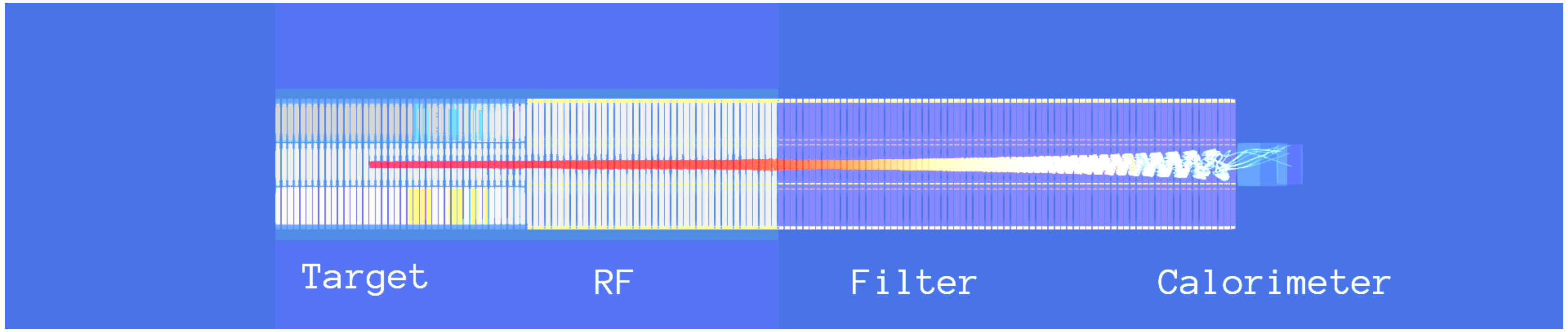
(Chris Tully, Princeton)

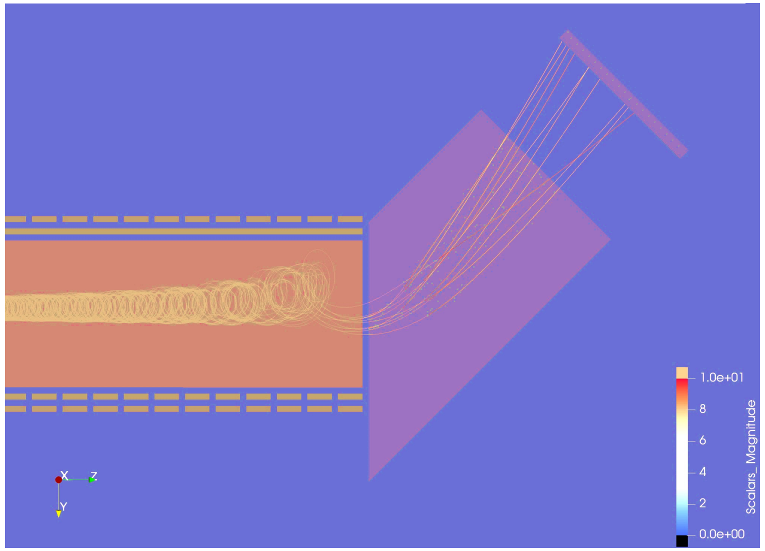


Transfer function, aperture, and sensitivity

- Geometric aperture studies completed with analytical filter fields
- Zero-field transition to microcalorimeter under study
- Transfer function simulations with LNGS demonstrator setup underway
- Sensitivity studies with theory input and LNGS demonstrator resolution in progress
- Mass-exposure capacity of LNGS demonstrator under study







PTOLEMY Timeline