Relic Neutrino detection with PTOLEMY

Take home: this will be tough

A.P. Colijn

Universiteit van Amsterdam

Nikhef

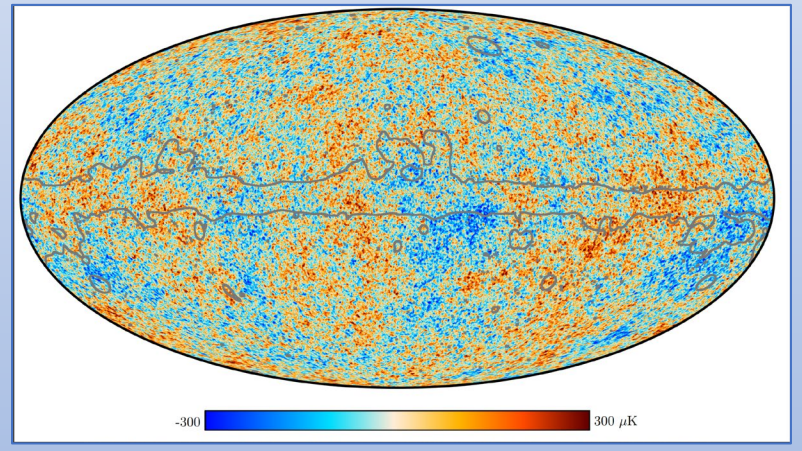
Universiteit Utrecht

Why believe Big Bang?

1. Expansion of Universe

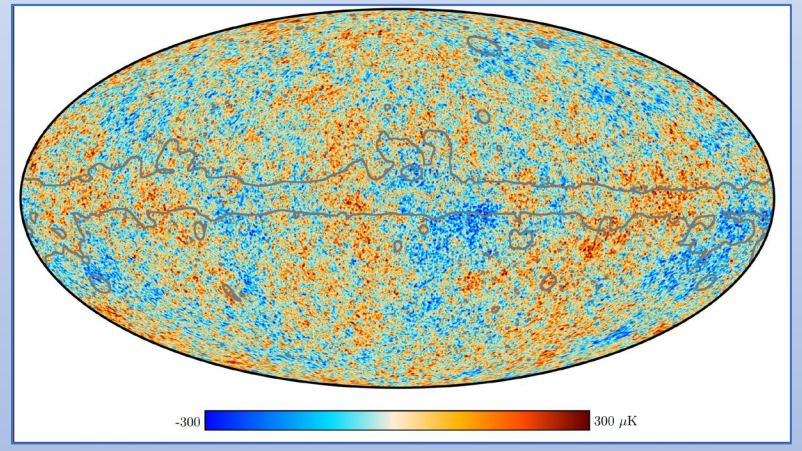
2. Light element abundances

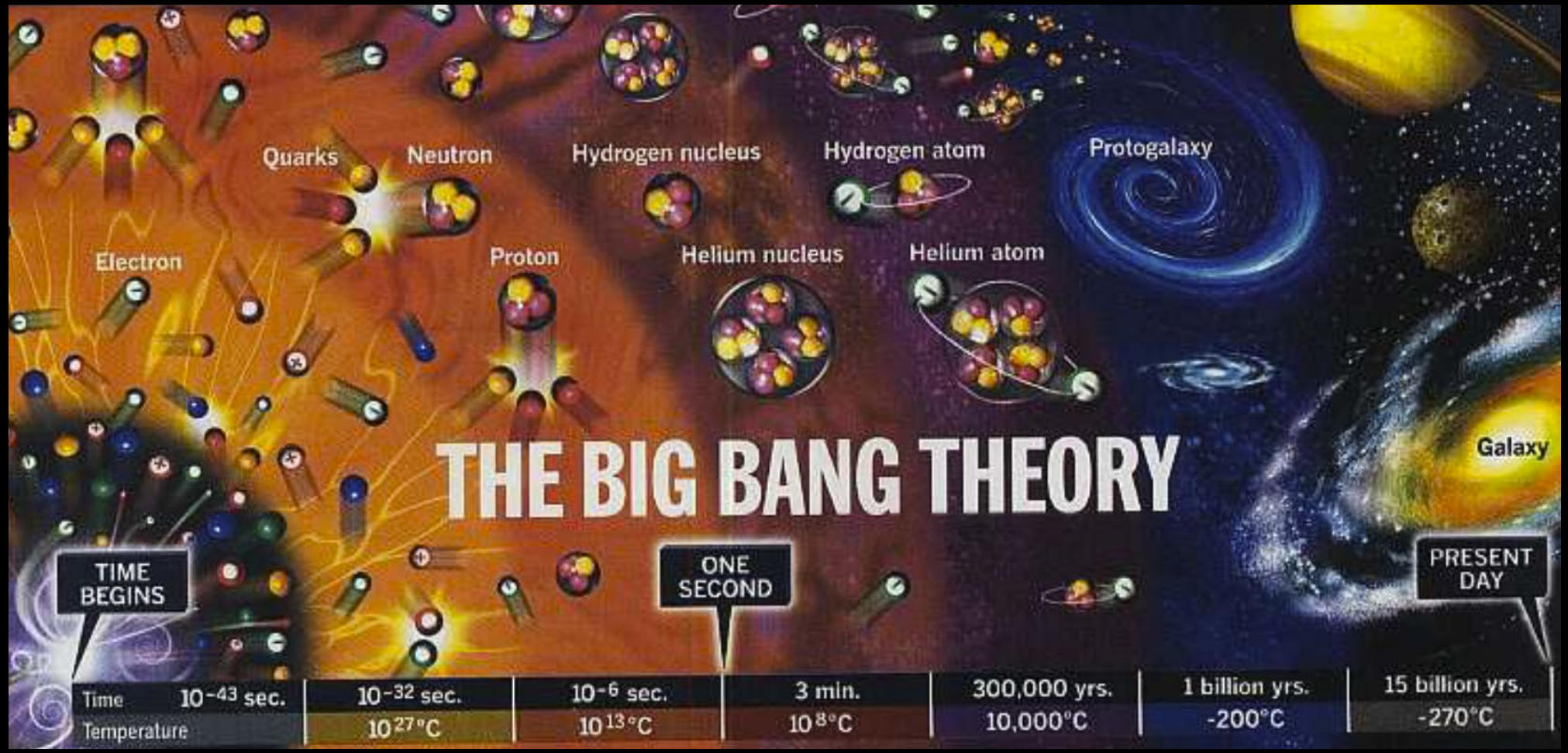
3. Cosmic Microwave Background



Why believe Big Bang?

1. Expansion of Universe
2. Light element abundances
3. Cosmic Microwave Background
4. **Cosmic Neutrino Background**



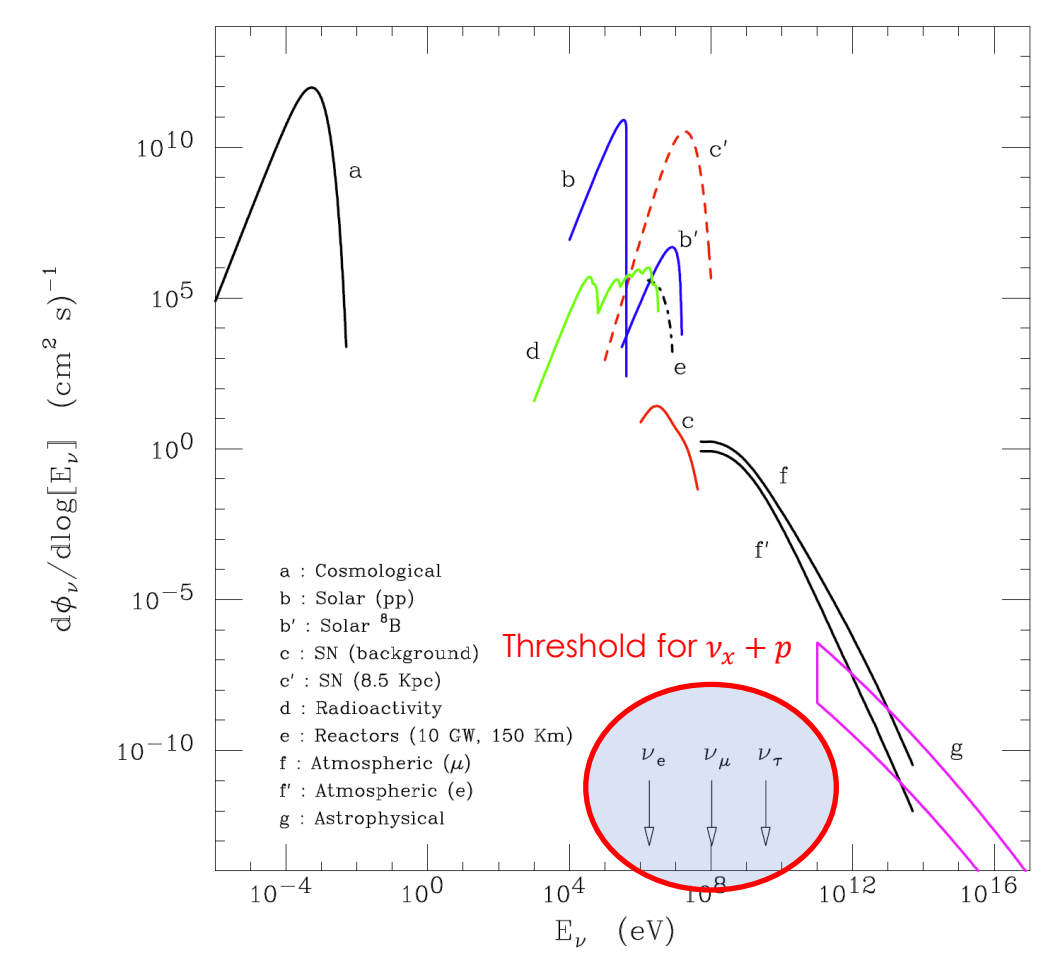


CNB ~ 1 sec

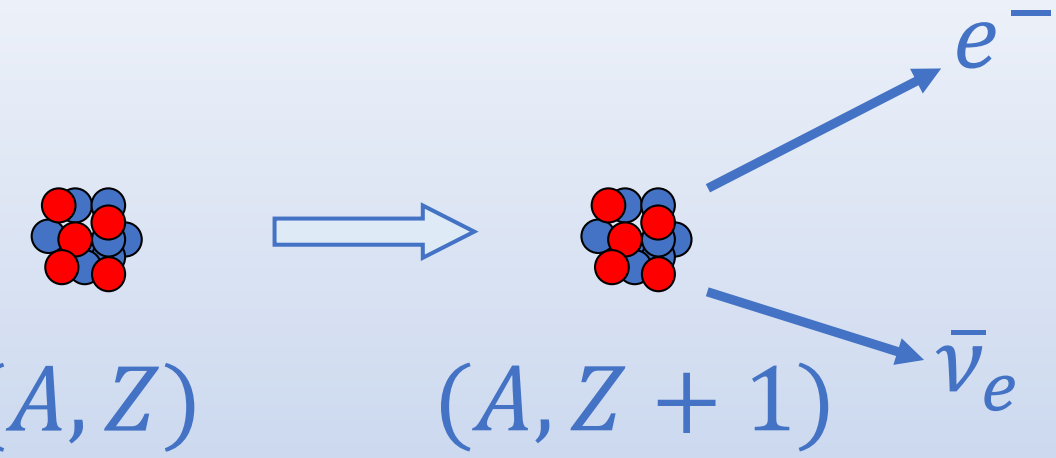
CMB ~ 380k yr

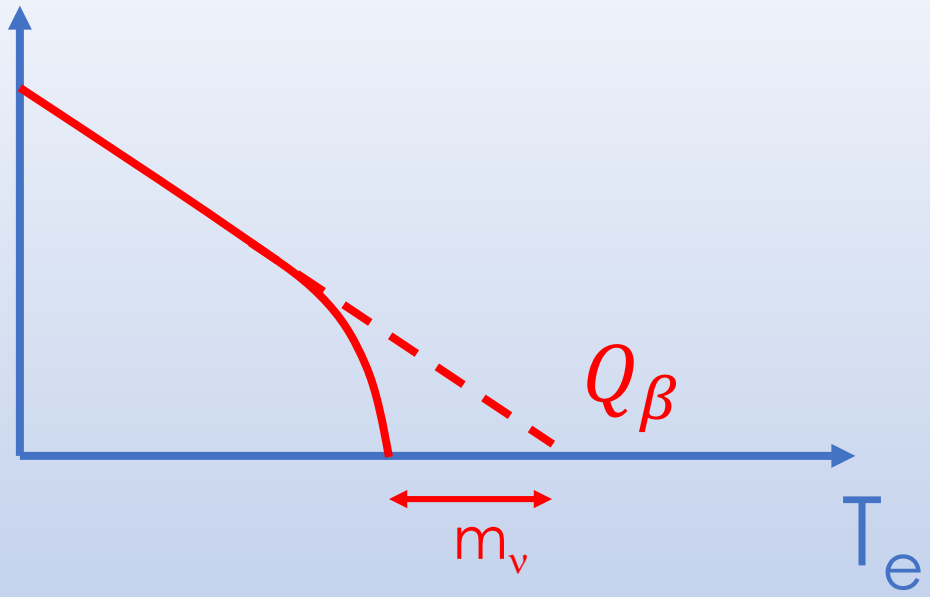
$$T \approx 1.9K \Rightarrow p_\nu \approx 0.001\ \text{eV}$$

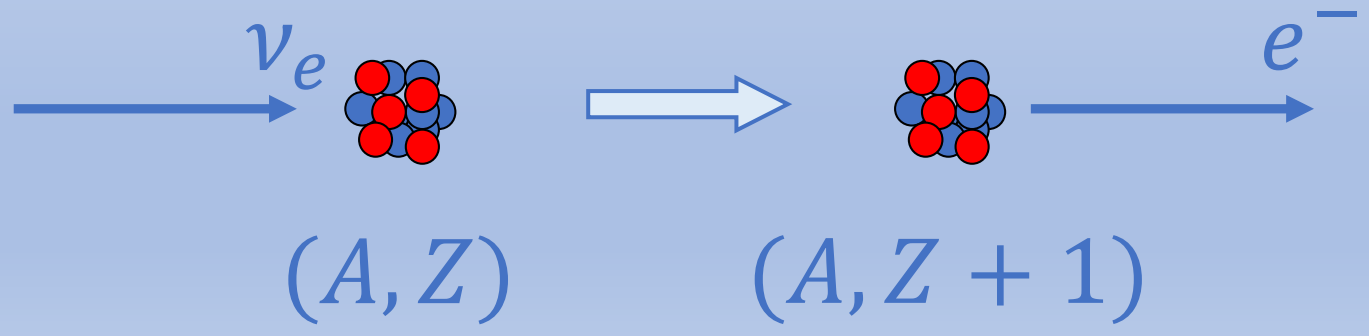
$$n \approx 56\ cm^{-3} \times 6$$

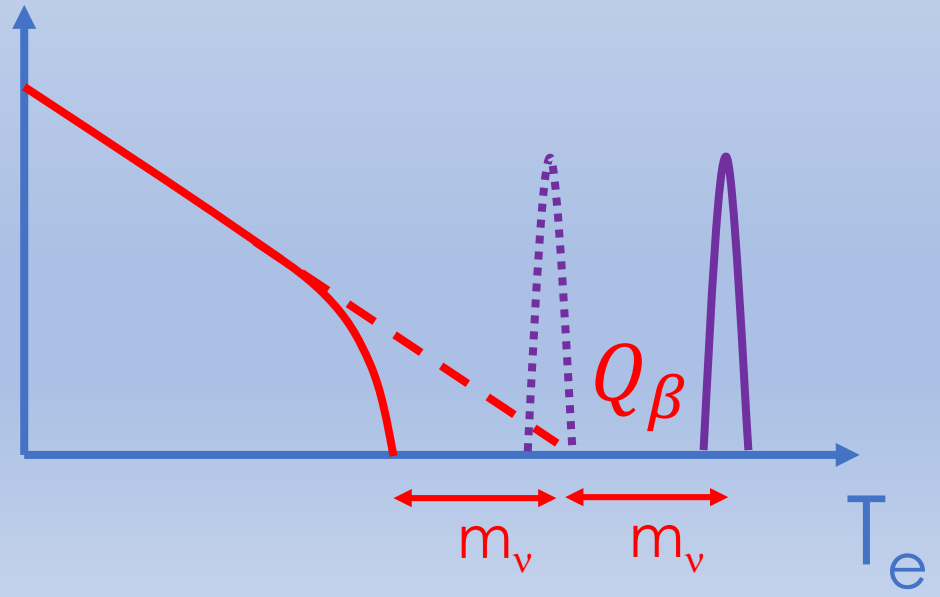


Is it possible to detect 0.001eV neutrinos?


e^-
$\bar{\nu}_e$
(A, Z)
$(A, Z+1)$


Q_β
m_ν
T_e

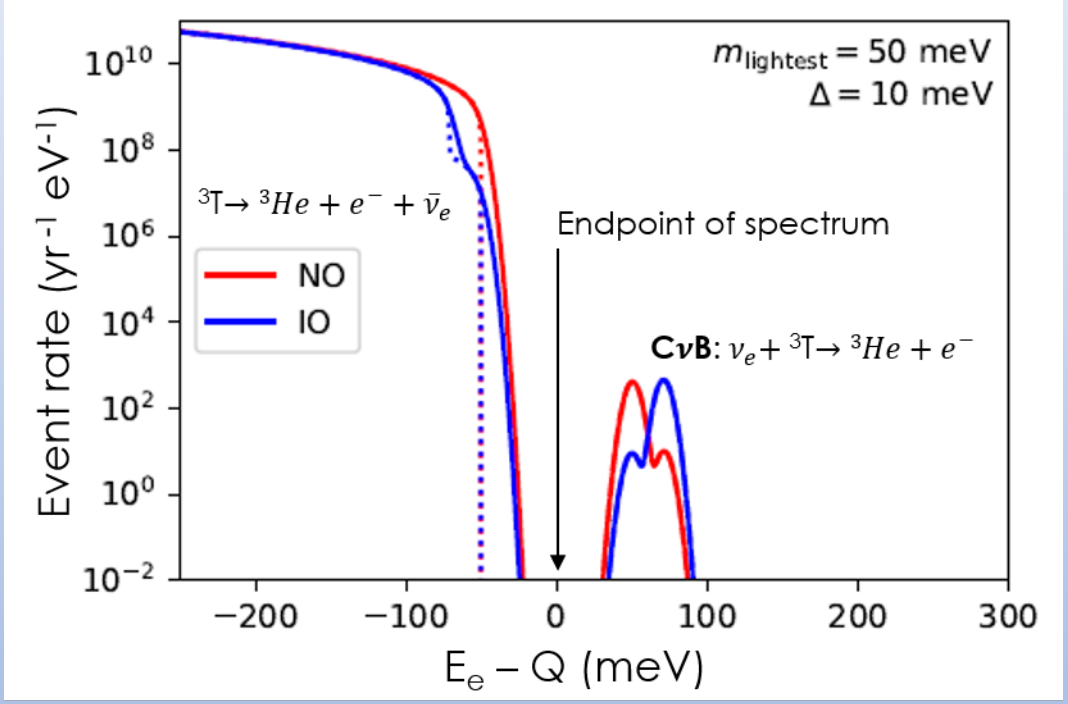

ν_e
e^-
(A, Z)
$(A, Z+1)$


Q_β
m_ν
m_ν
T_e

Tritium

$\nu_e \longrightarrow {}^3T$ $\qquad$ ${}^3He \longrightarrow e^-$

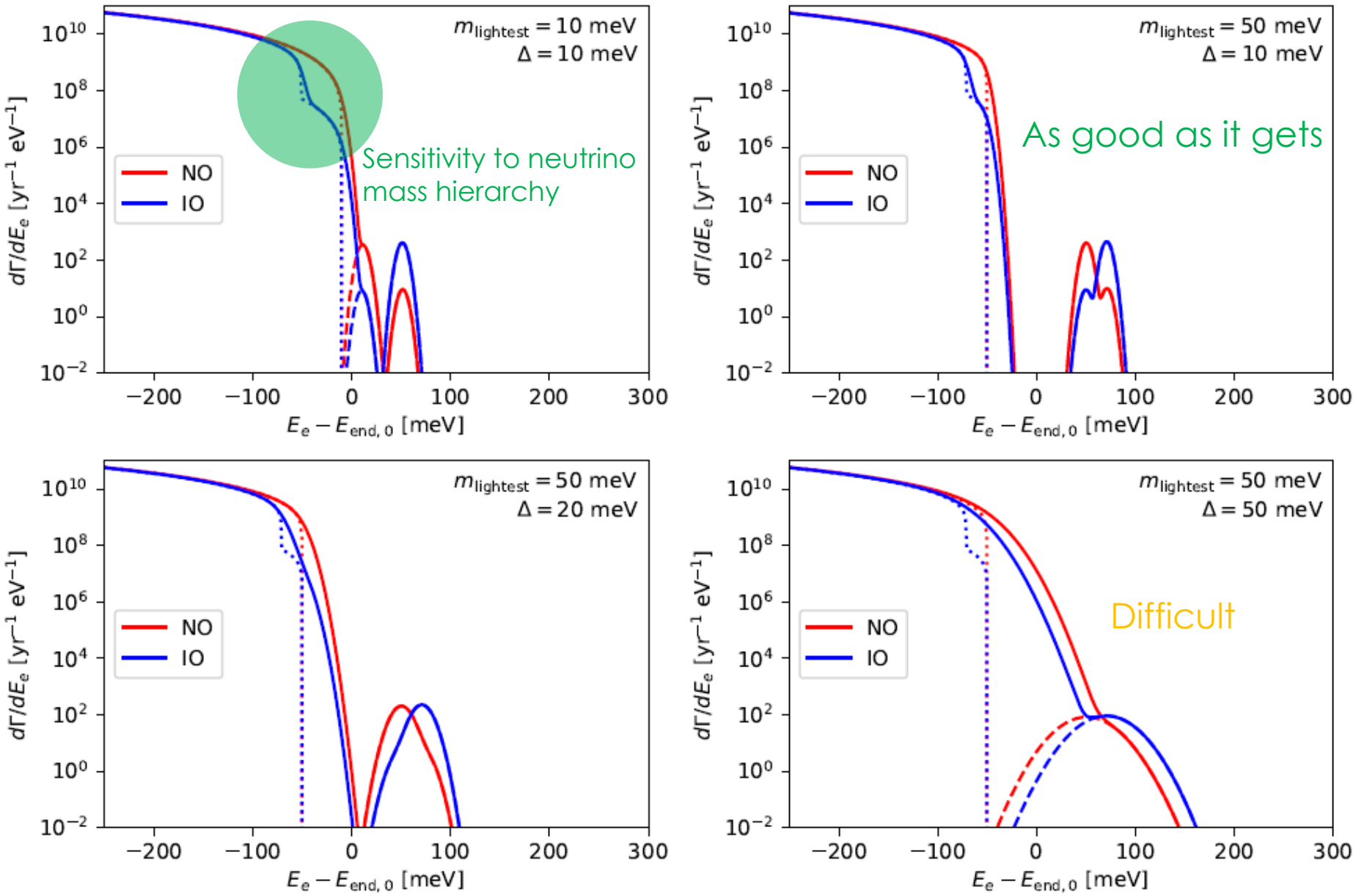
- High cross-section for neutrino capture
- Sizeable lifetime
- Low Q-value of 18.6 keV
- **Tritium beta decay ~10^{15} Bq/gram**
- **100g tritium gives 10-100 ev /yr**



m_ν (eV)	FD (events yr^{-1})	NFW (events yr^{-1})	MW (events yrs^{-1})
0.6	7.5	90	150
0.3	7.5	23	33
0.15	7.5	10	12

https://arxiv.org/abs/hep-ph/0703075

Several σ_E and m_ν scenarios



PTOLEMY experiment

- Goal:

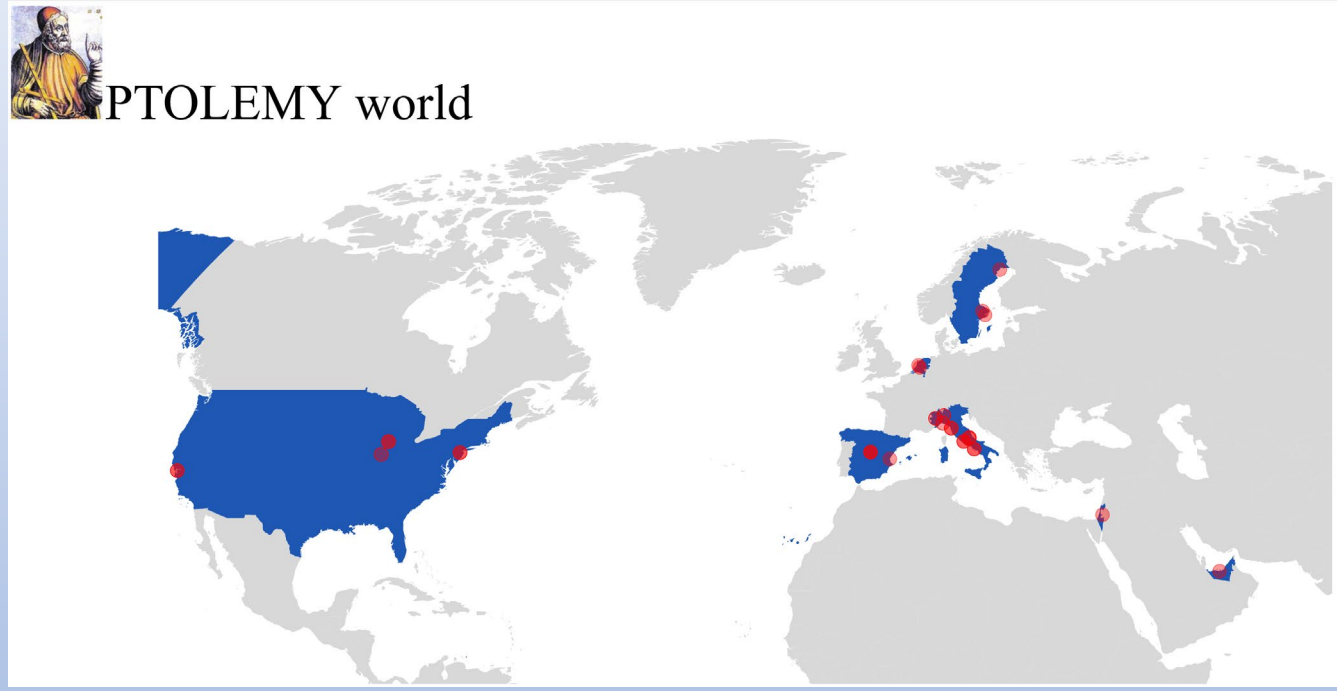
  1. Find evidence for $C\nu B$
  2. Accurate measurement of neutrino mass
  3. Light DM detection (not discussed in this talk)

- Experimental challenges:

  1. Extreme energy resolution
  2. Extreme background rates

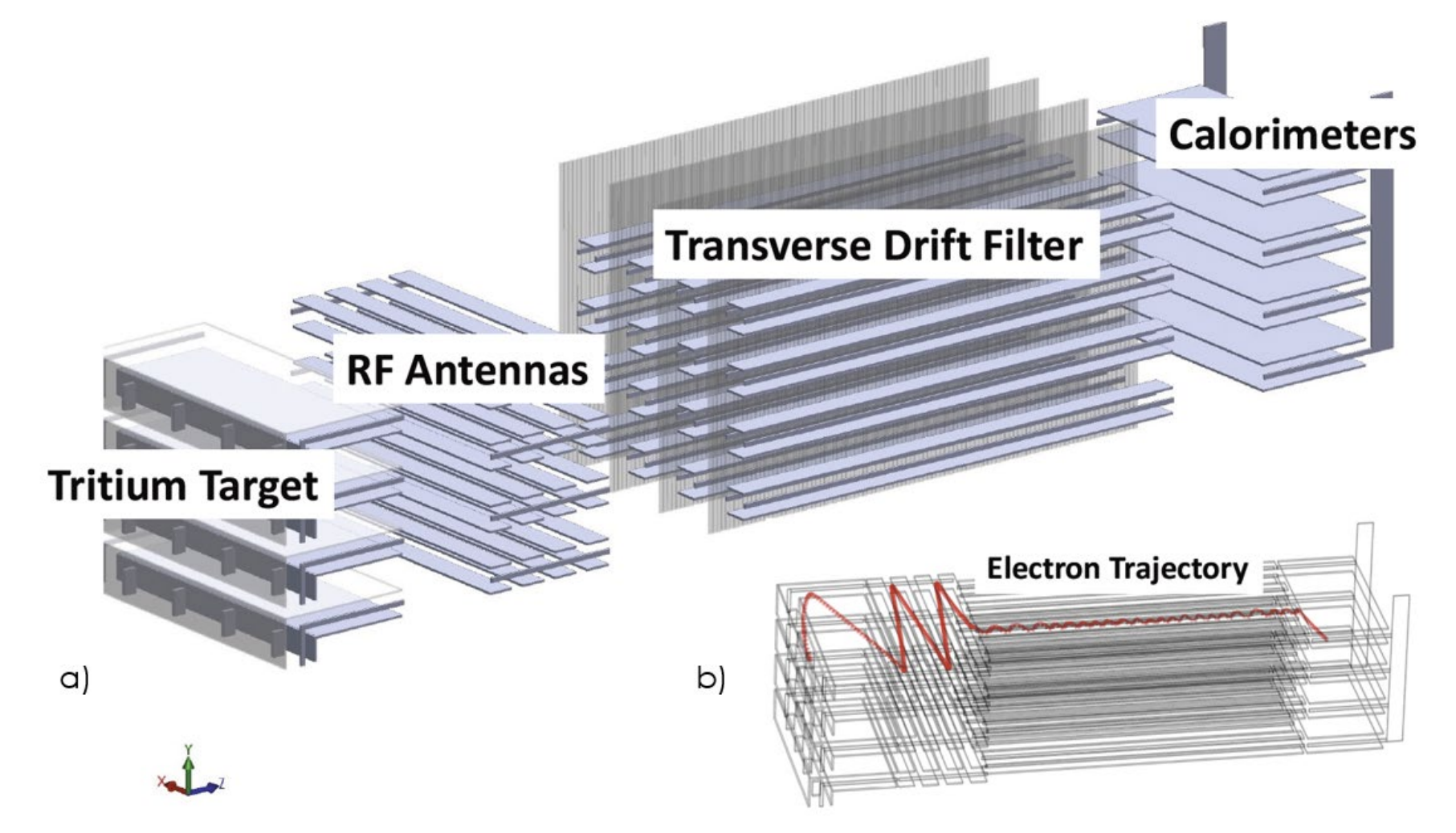
- In case you loose track:

  Think of Photo-Electric effect measurements



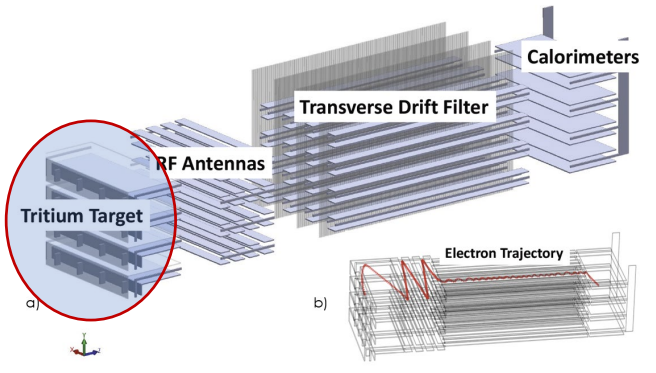
https://www.nikhef.nl/~z37/PTOLEMY_collaboration_viewer/PTOLEMY_world.html

PTOLEMY: main components



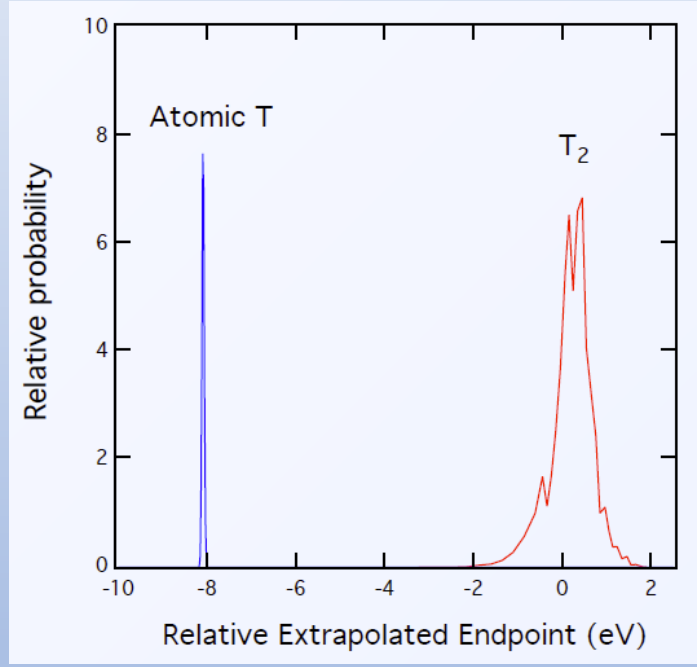
Princeton
Tritium
Observatory for
Light
Early-universe
Massive neutrino
Yield

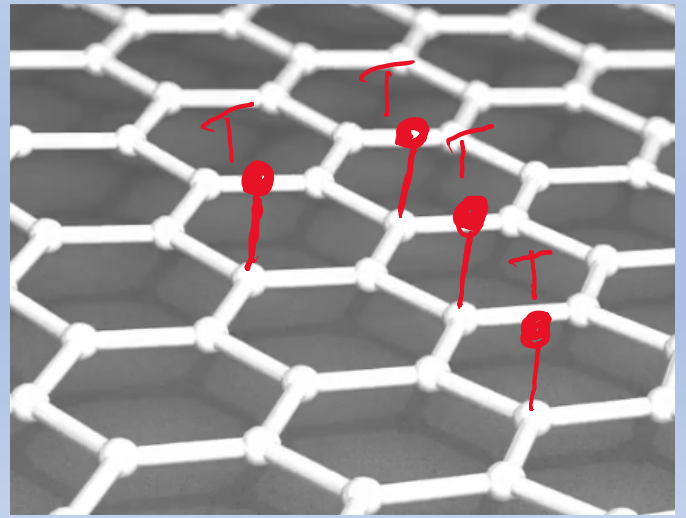
PTOLEMY: tritium target



- Use **atomic ^{3}T**
  - No ro-vibrational modes in final state like for ^{3}He-^{3}T final state.
  - Limit to energy resolution not determined by target itself

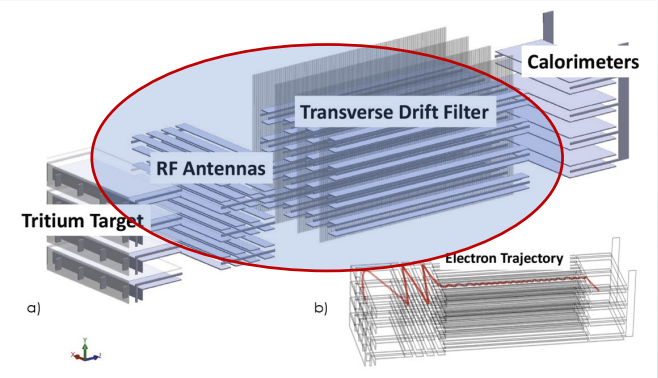
- dE/dx of electrons requires extremely **thin targets**
- We investigate ^{3}T loosely bound to graphene (or Cu, or Au)
  - Theoretical maximum is about 0.2 mg tritium per m^2



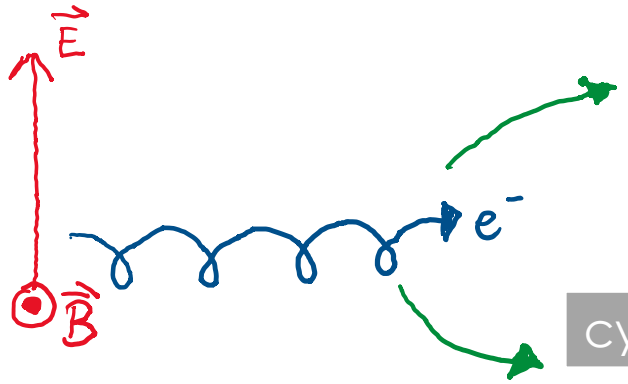


Max 1-tritium for every C

PTOLEMY: two types of drift



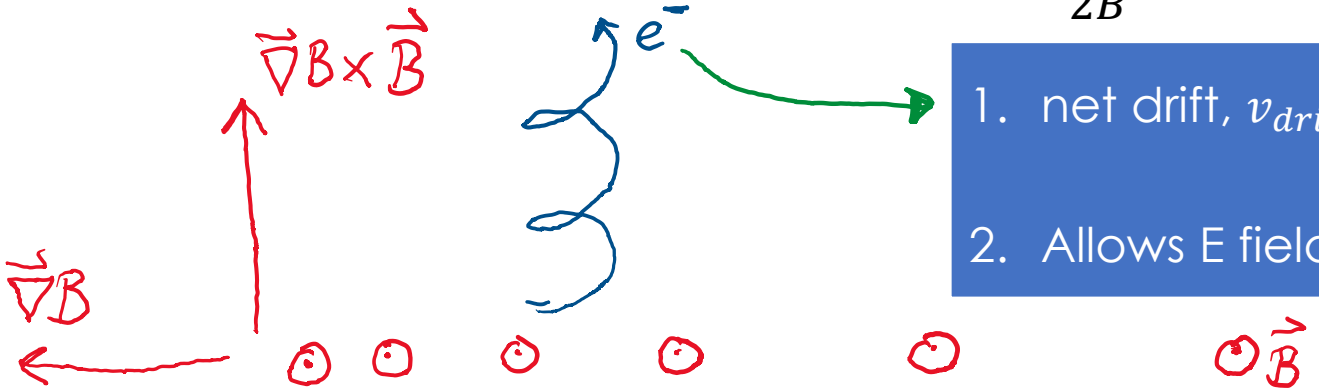
I: $\vec{E} \times \vec{B}$ drift



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

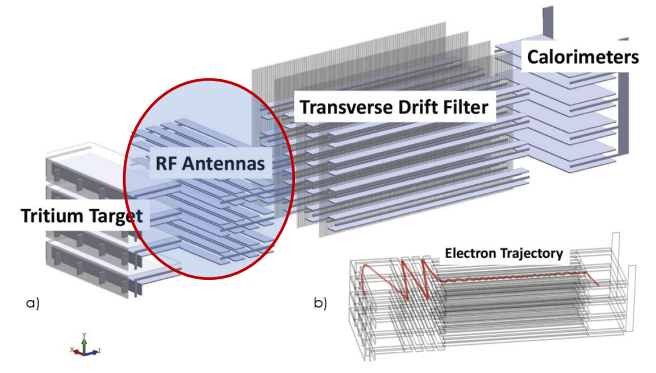
cyclotron motion – detectable RF

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

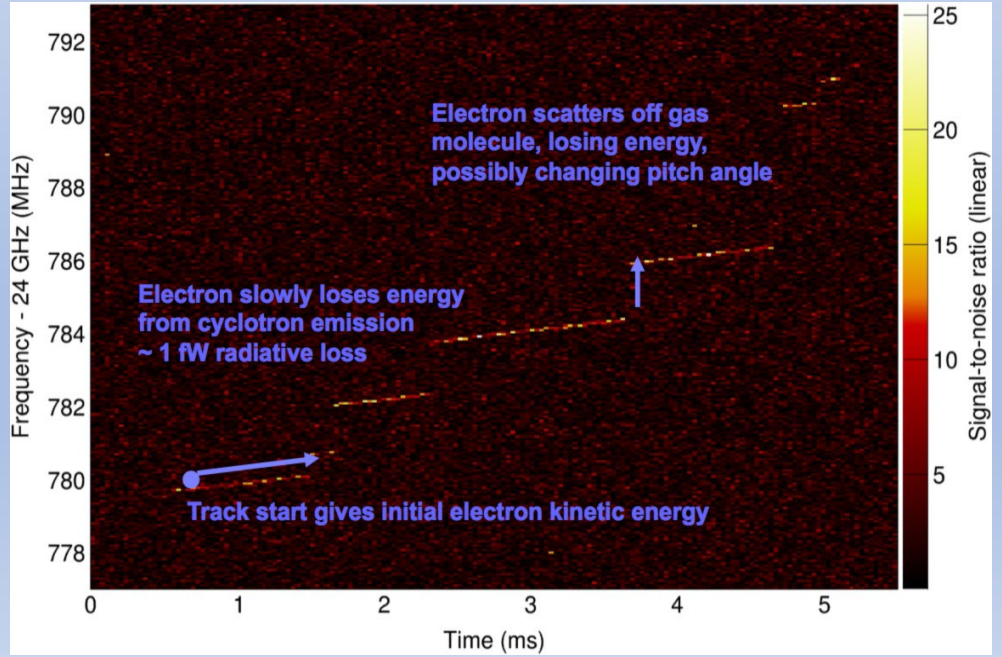


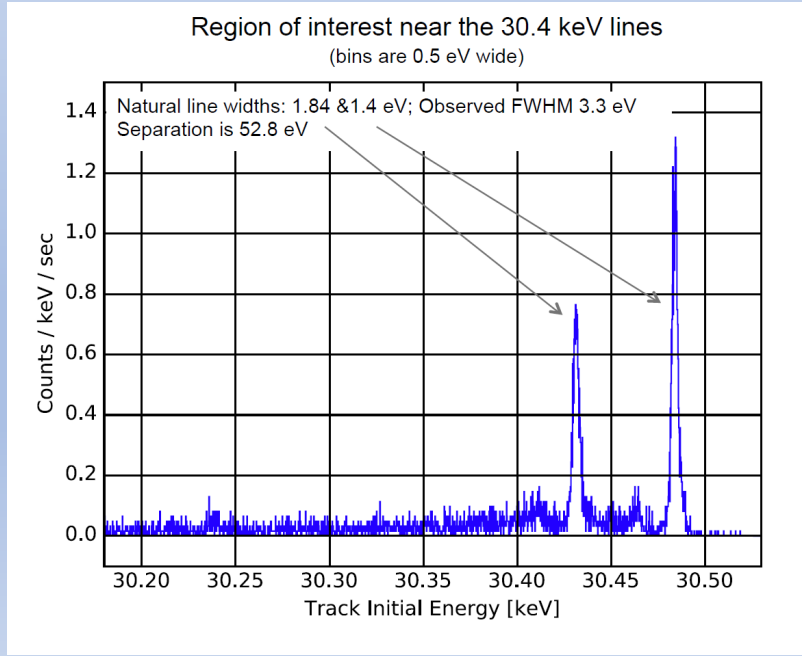
1. net drift, $v_{drift} = \mu \frac{|\vec{\nabla}B|}{B}$
2. Allows E field to work (!): $\frac{dT_\perp}{dt} = e\vec{E} \cdot \vec{v}_{drift}$

PTOLEMY: RF pickup



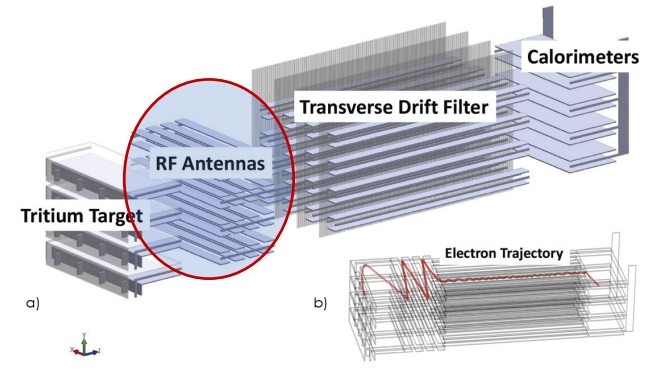
- Transport electrons through **ExB** field
- RF emission with $f = \frac{1}{2\pi}\frac{eB}{m_e\gamma} \approx 24GHz \rightarrow \gamma =$ Energy
- Power $P = \frac{1}{4\pi\epsilon_0}\frac{2e^4B^2}{3m_e^2c}(\gamma^2-1)\sin^2\theta \approx 1\,fW \rightarrow \theta$ is angle between B and $\vec{\beta}$





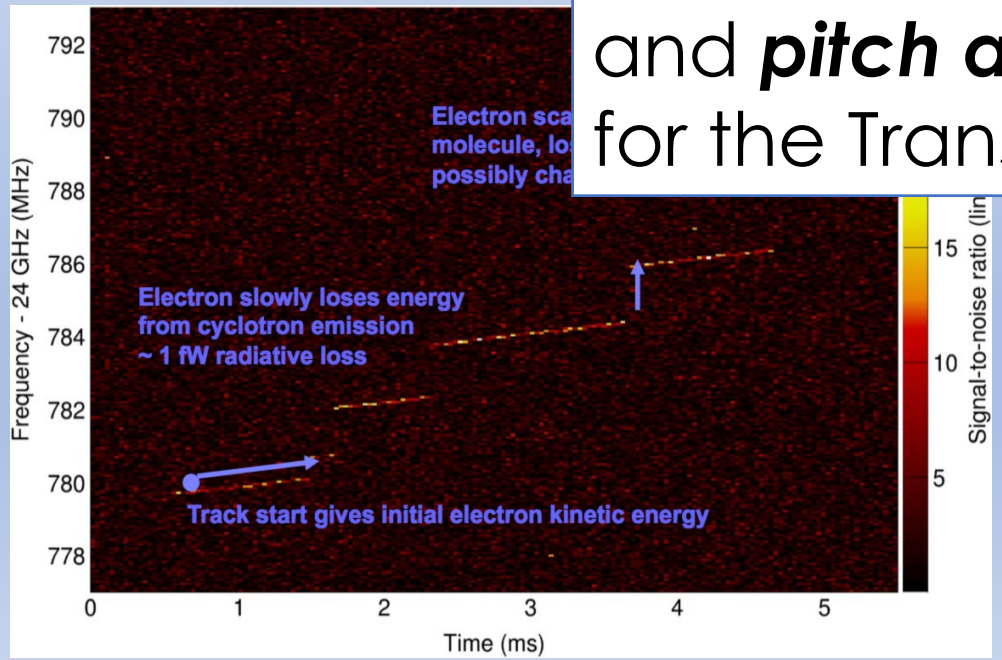
Pioneering work by Project8 @ FNAL
A.Esfahani et. al, JPG Vol44,#5, 2017
https://arxiv.org/abs/1703.02037v1

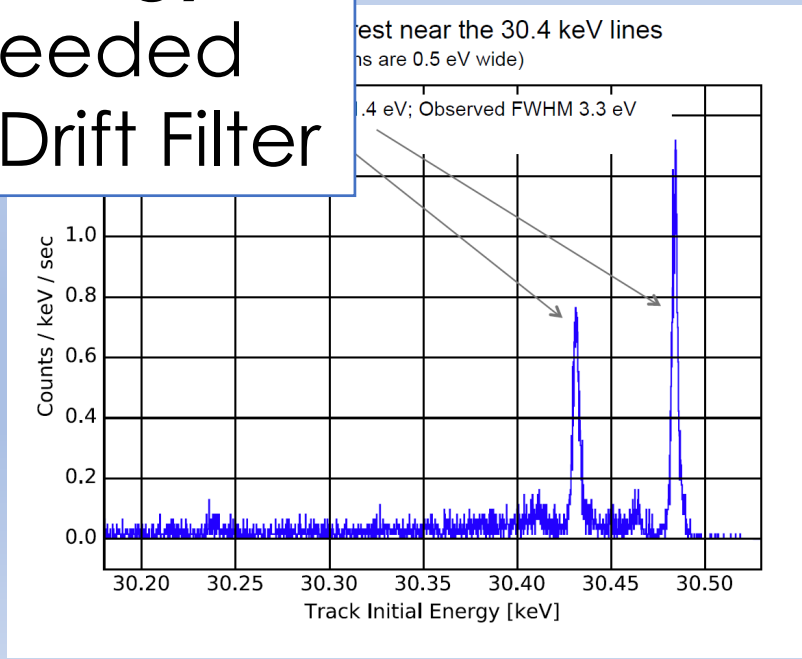
PTOLEMY: RF pickup



- Transport electrons through **ExB** field
- RF emission with $f = \frac{1}{2\pi}\frac{eB}{m_e\,\gamma} \approx 24GHz \rightarrow \gamma = \text{Energy}$
- Power $P = \frac{1}{4\,\pi\epsilon_0}\frac{2\,e^4}{3m}$ … veen B and $\vec{\beta}$

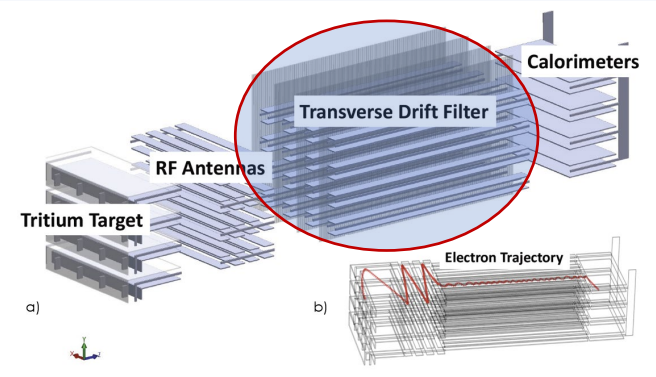
Rough O(eV) resolution (!) measurement of ***energy*** and ***pitch angle*** needed for the Transverse Drift Filter

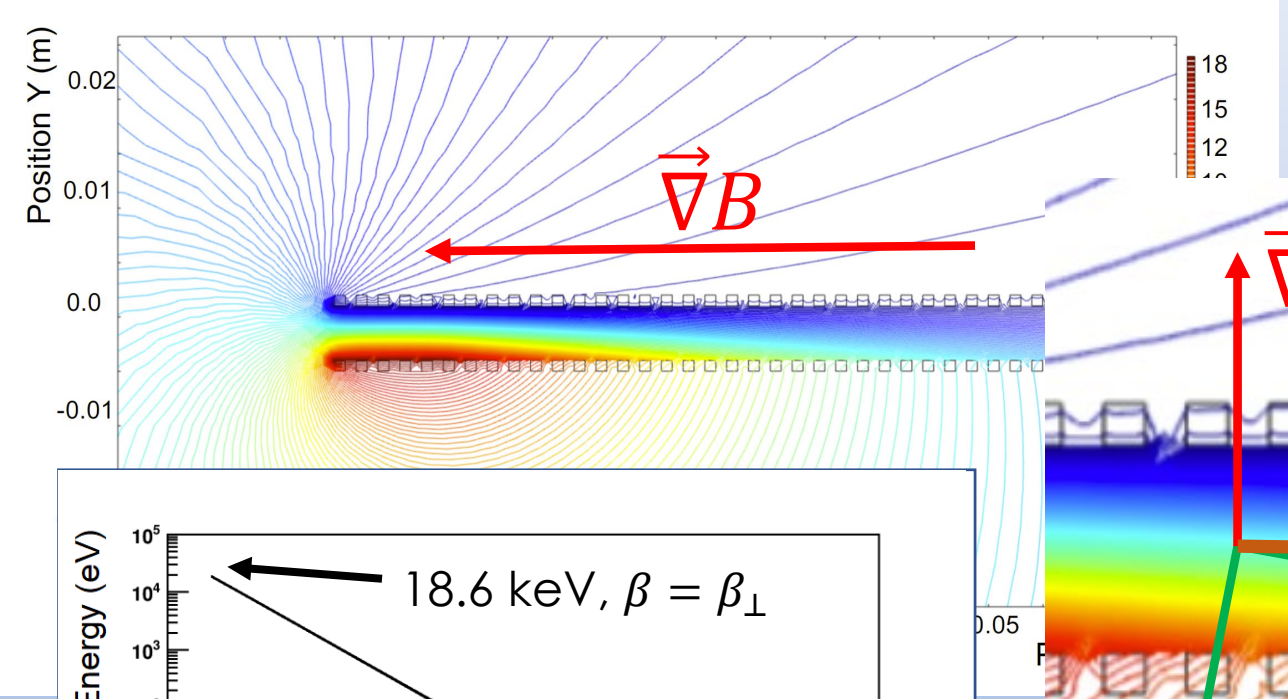


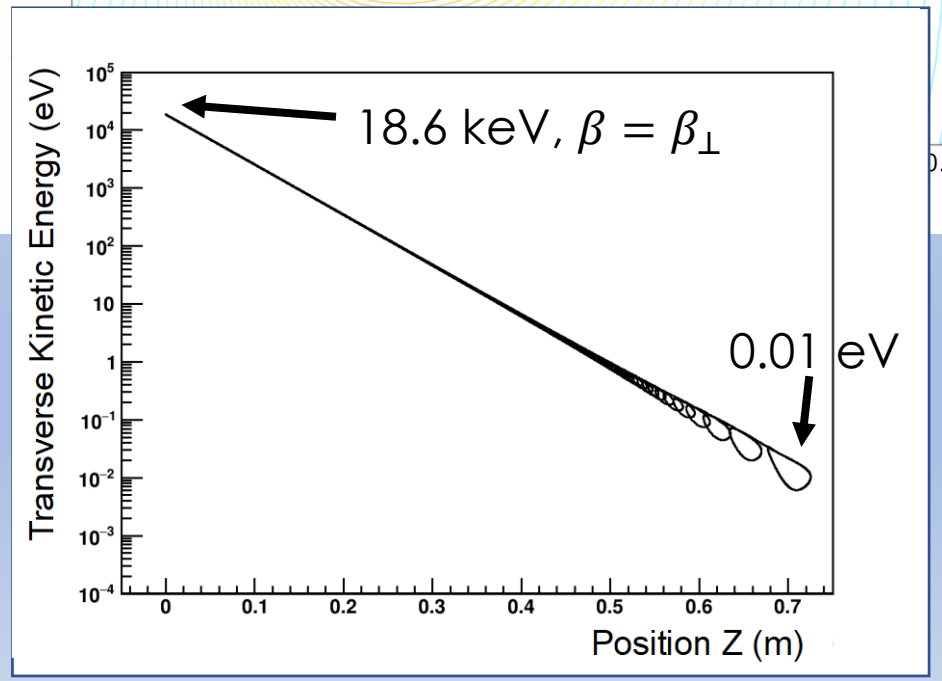


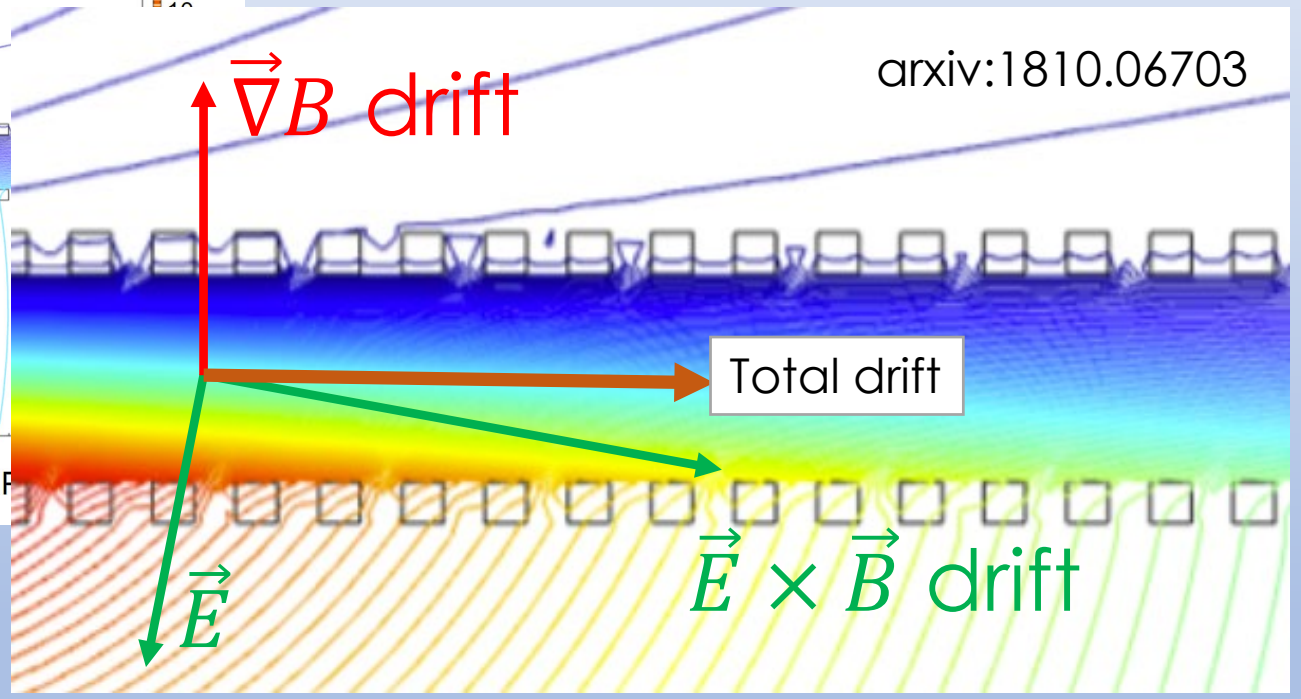
Pioneering work by Project8 @ FNAL
A.Esfahani et. al, JPG Vol44,#5, 2017
https://arxiv.org/abs/1703.02037v1

PTOLEMY: Transverse drift filter





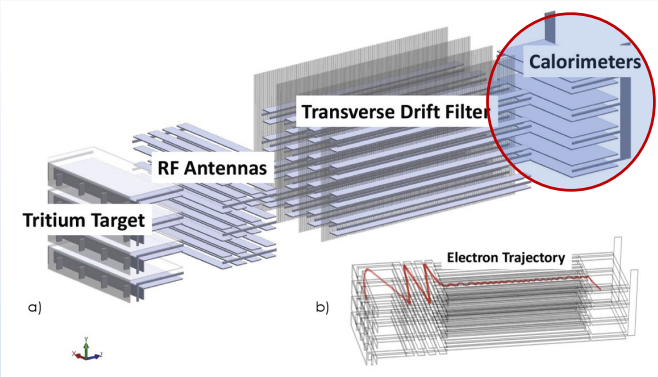




After filter, only component of β parallel to B is left.

Can be reduced by retarding potential

PTOLEMY: Energy



- Energy measurement from ΔV and calorimeter:

$$E_e = e\,(V_{cal} - V_{source}) + E_{cal}$$

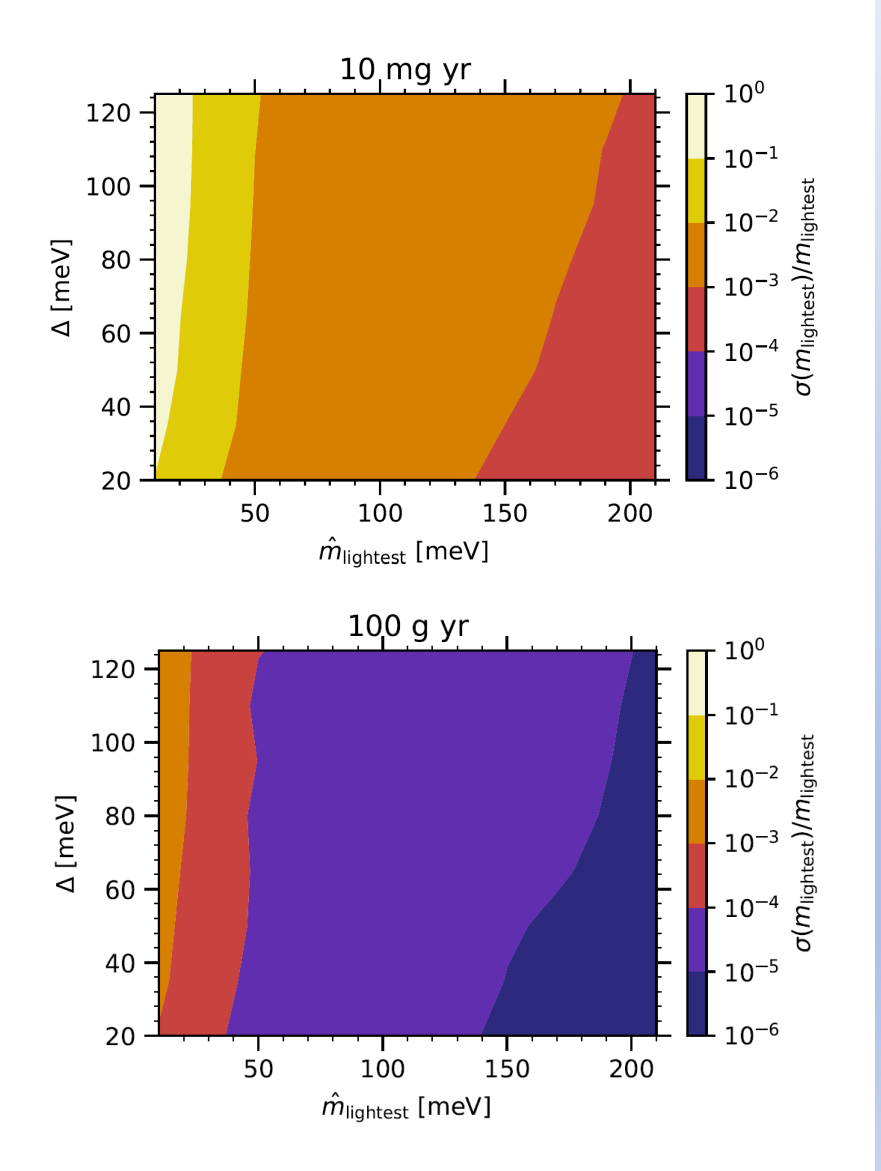
- Calorimeter energy resolution must be O(50meV)
  1. Transition Edge Sensors
  2. State-of-the-art 2019 O(100meV@100eV)

- Voltage stability over experiment better than 10mV

- NOTE: internal voltages are actively adjusted for each interesting electron

PTOLEMY: m_ν expected performance

- Neutrino mass as first result
  1. Small exposure already gives sensitivity to O(10meV) m_ν
  2. Crucial for design of full scale $C\nu B$ PTOLEMY with 100g tritium
- Mass hierarchy
  1. Clearly decided with 100g yr exposure
  2. Up to masses <100meV



arxiv:1902.05508

PTOLEMY: m_ν expected performance

Measurement of m_ν is key to design of full scale PTOLEMY experiment

t

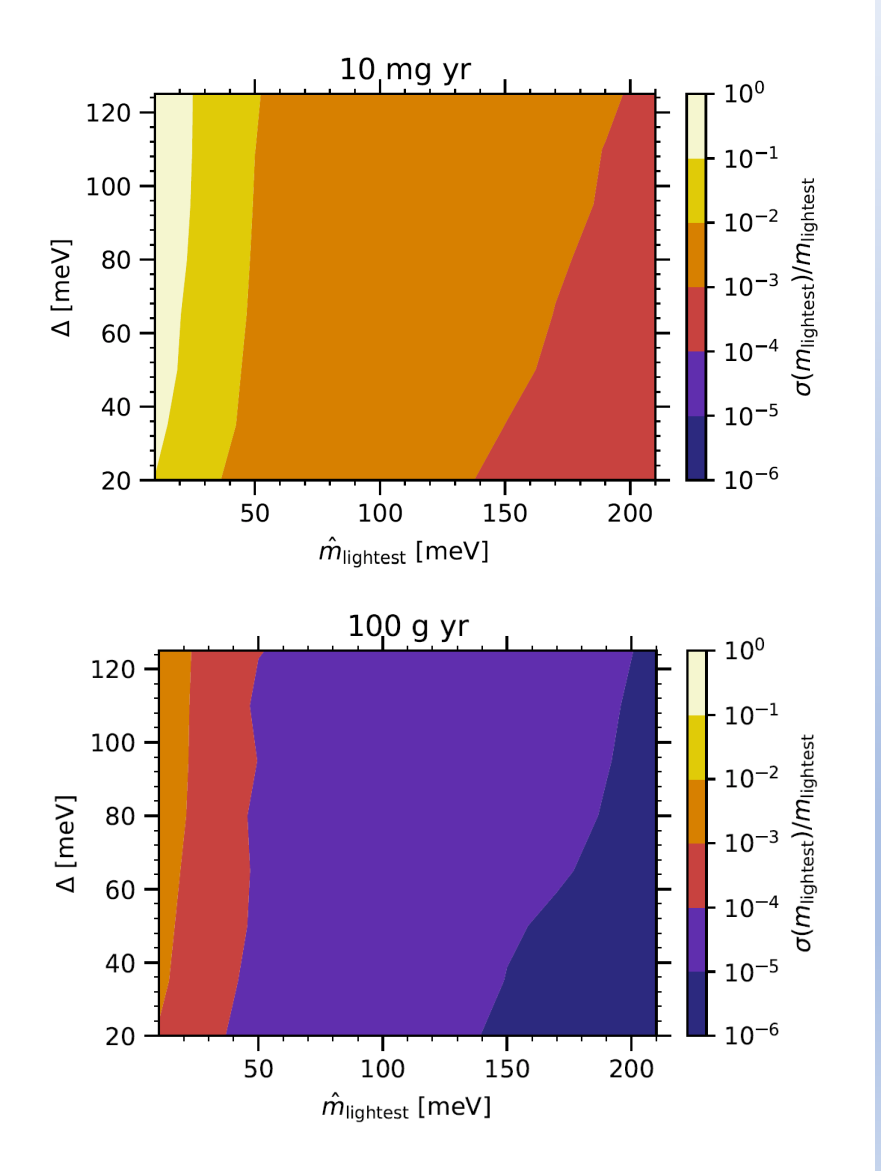
sensitivity to O(10meV) m_ν

2. Crucial for design of full scale $C\nu B$ PTOLEMY with 100g tritium

- Mass hierarchy

1. Clearly decided with 100g yr exposure

2. Up to masses <100meV

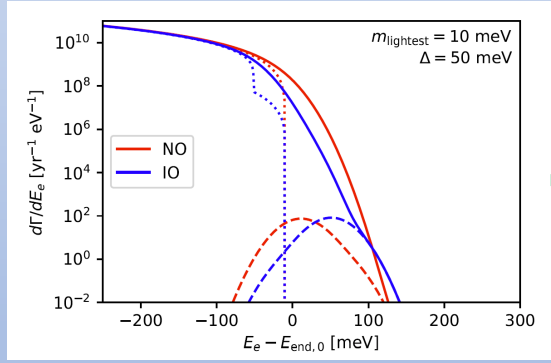


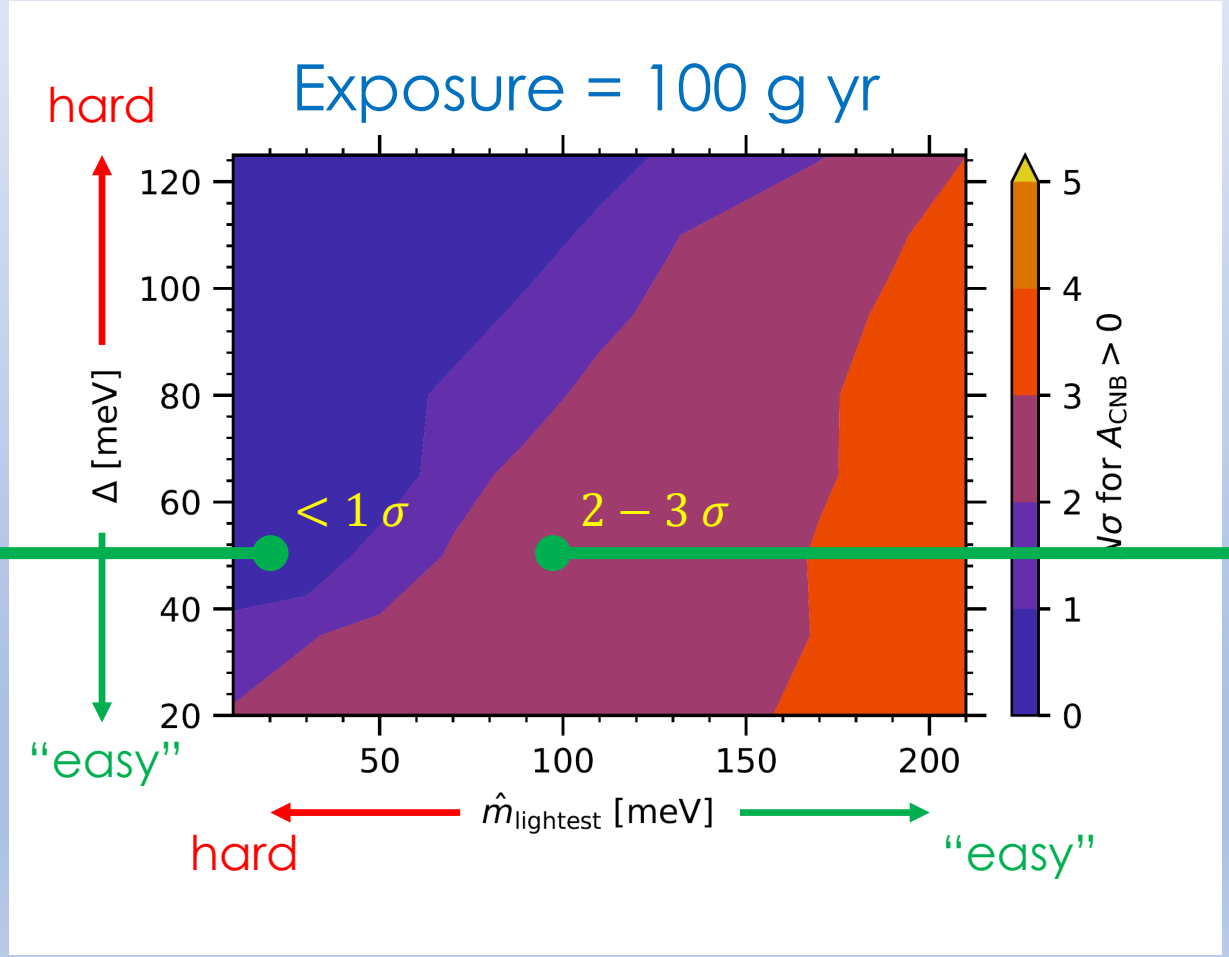
arxiv:1902.05508

PTOLEMY: $C\nu B$ expected performance

$m_\nu^{lightest} = \mathbf{10\ meV}$

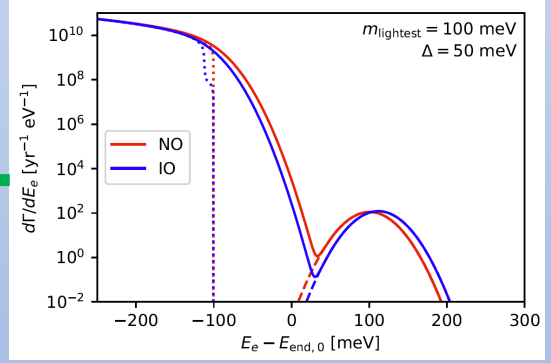
$\Delta = 50\ meV\ (\sigma_E = 20\ meV)$





$m_\nu^{lightest} = \mathbf{100\ meV}$

$\Delta = 50\ meV$



arxiv:1902.05508

Demonstrator facility at the Gran Sasso above ground laboratory

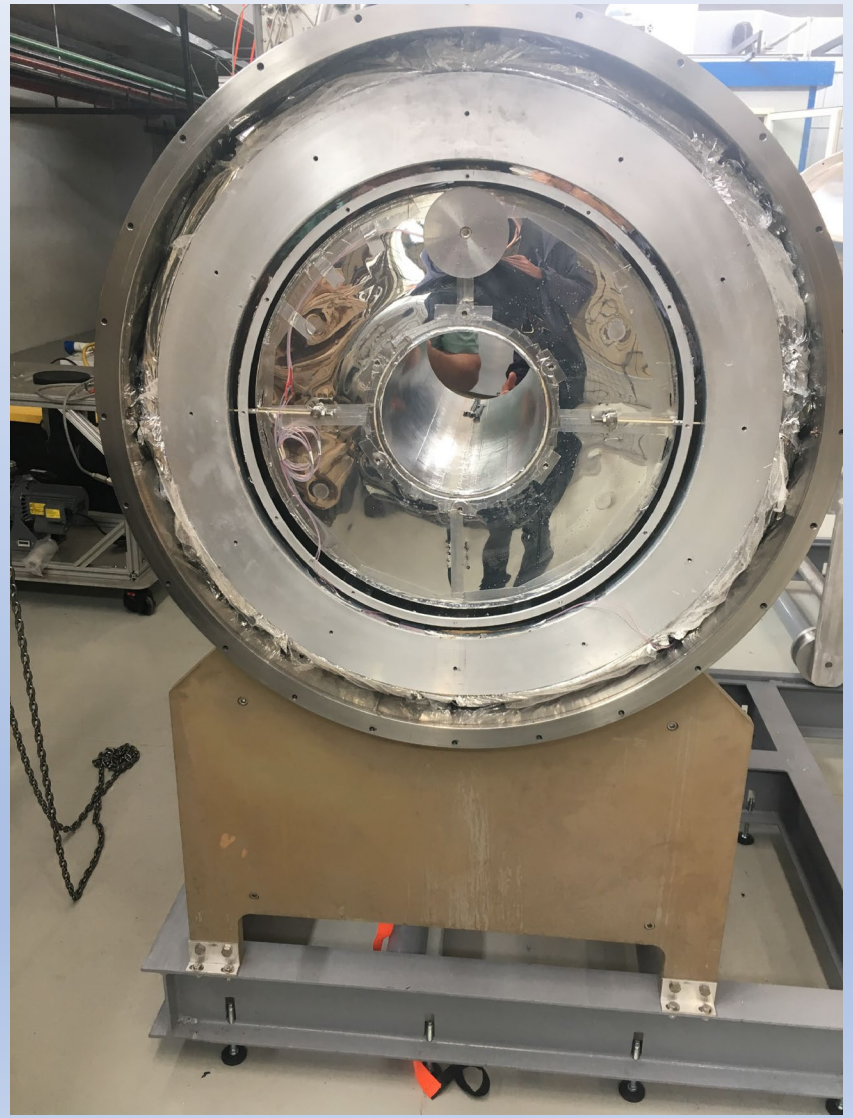
PTOLEMY

R&D Prototype @ PPPL
(August 2, 2016)

Supported by:
The Simons Foundation
The John Templeton Foundation

PTOLEMY

Now at LNGS



PTOLEMY

1. Different

2. Physics program:
   1. **Relic Neutrino's**
   2. **Neutrino mass**
   3. **Light DM**

3. Technological challenges:
   1. **Extreme high rate**
   2. **Extreme energy resolution**