Relic Neutrino detection with PTOLEMY

Auke-Pieter Colijn

Rome 30-01-2023

nationale wetenschaps agenda

Universiteit van Amsterdam

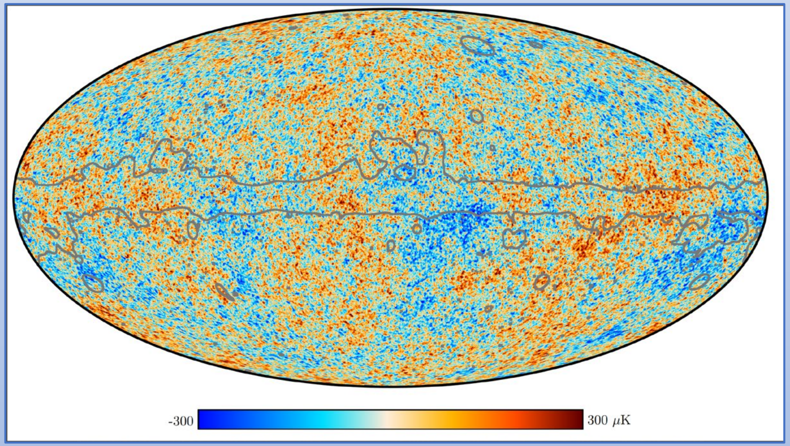
Nikhef

Why believe Big Bang?

1. Expansion of Universe

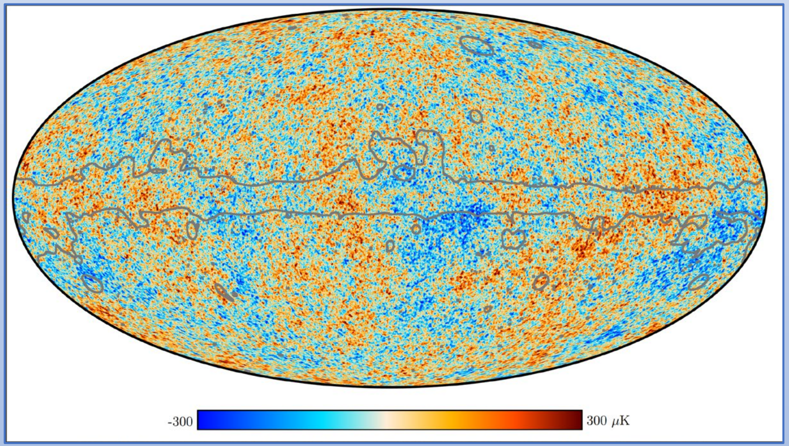
2. Light element abundances

3. Cosmic Microwave Background



Why believe Big Bang?

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



Big Bang

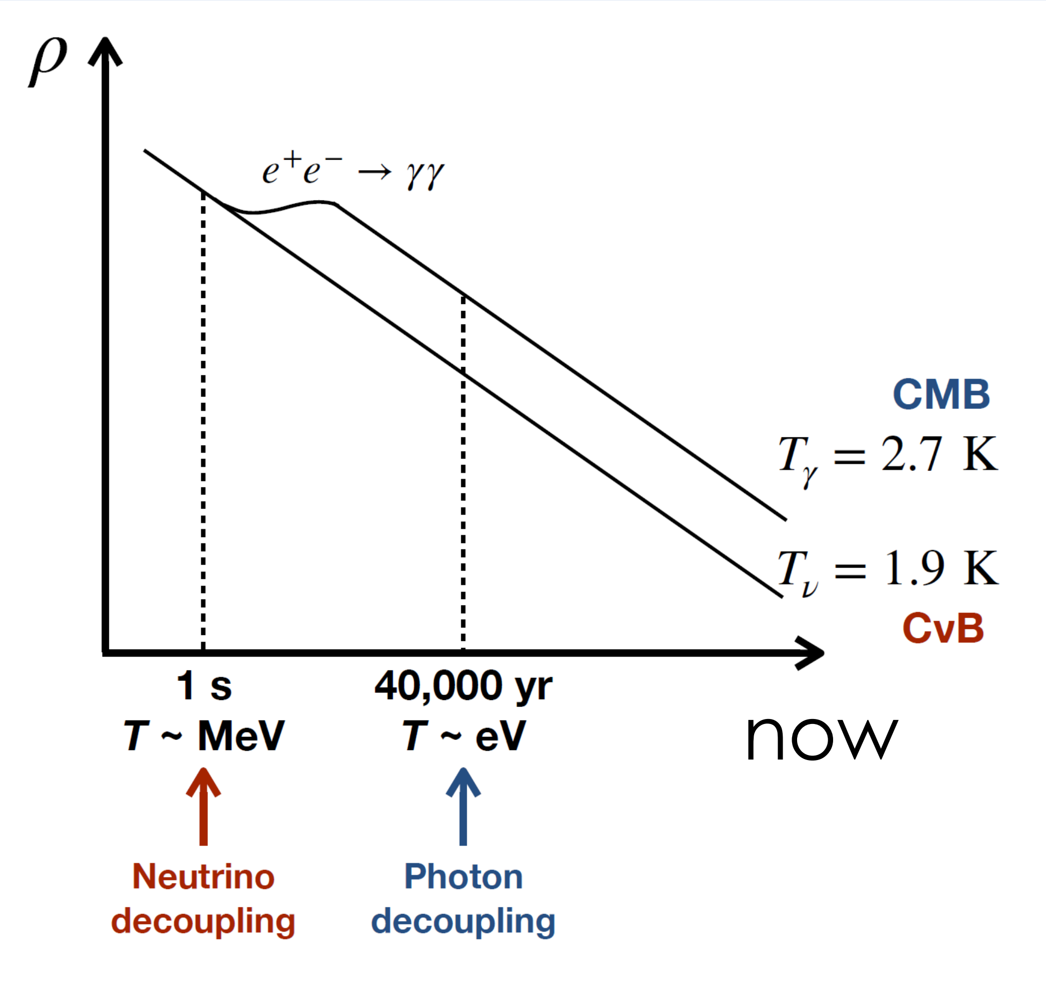
10^{-36} sec

1 sec

380.000 year

30 January 2023

Evolution of the relic neutrinos



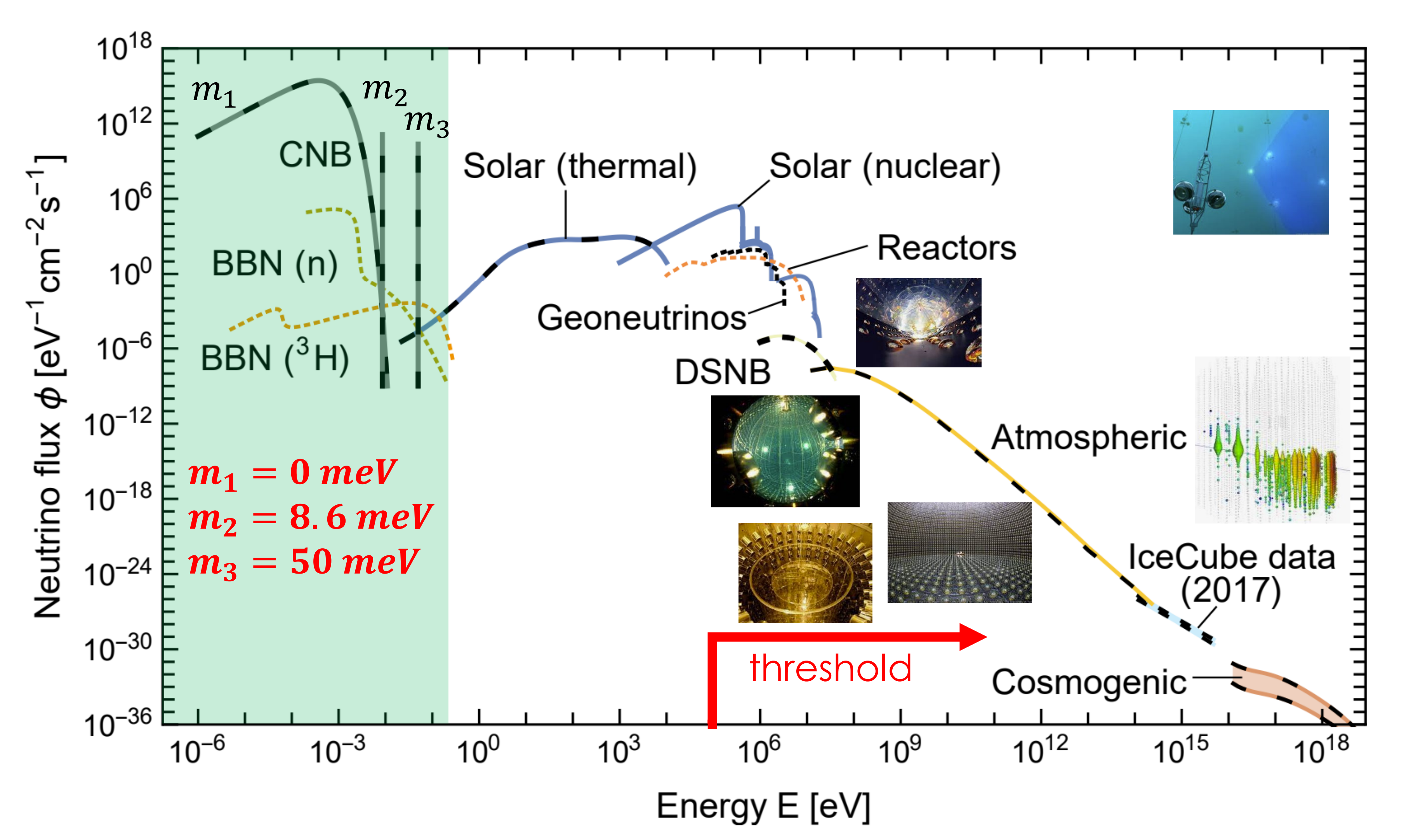
$C\nu$B and CMB temperature related:

$$\frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{\frac{1}{3}}$$

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

$$n_\nu + n_{\bar{\nu}} \approx 56\,cm^{-3} \times 6$$

Grand Unified Neutrino Spectrum



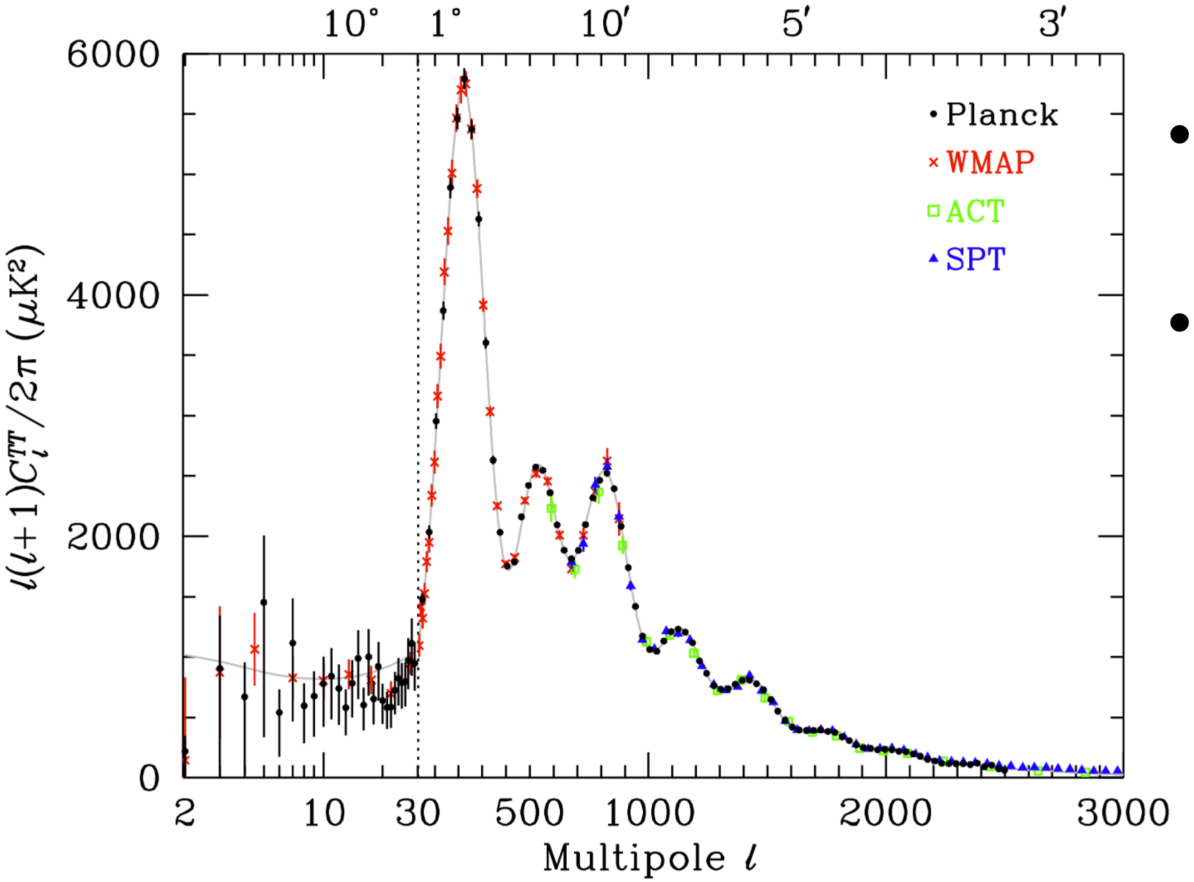
https://arxiv.org/pdf/1910.11878.pdf

Where to look for $C\nu B$?

- or –

Is it possible to detect 0.001eV neutrinos?

1. Early Universe & beyond



- $N_{eff} \approx 3$. They exists
- $\Sigma m_\nu \leq 0.12eV$. They are light.

nature physics

ARTICLES

https://doi.org/10.1038/s41567-019-0435-6

First constraint on the neutrino-induced phase shift in the spectrum of baryon acoustic oscillations

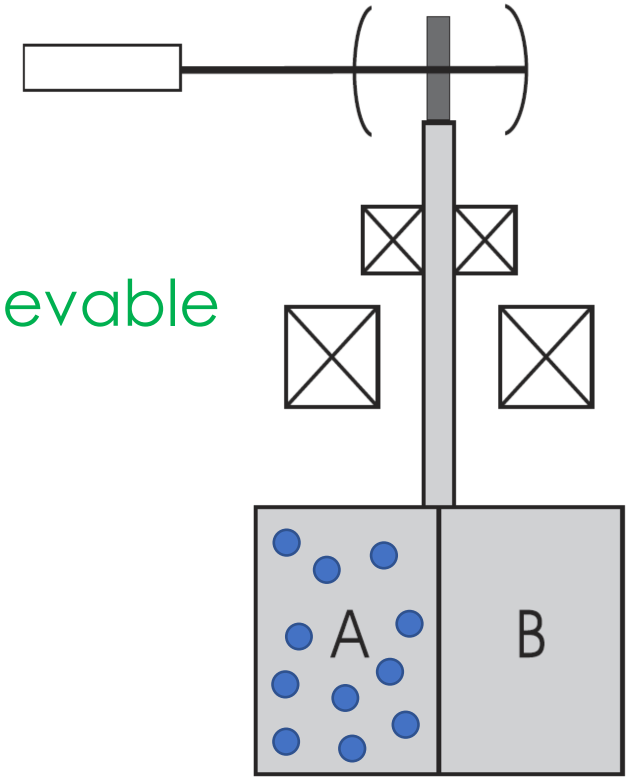
Daniel Baumann[1], Florian Beutler[2,3], Raphael Flauger[4], Daniel Green[4*], Anže Slosar[5], Mariana Vargas-Magaña[6], Benjamin Wallisch[1,7] and Christophe Yèche[3,8]

2. Neutrino wind – coherent scatter

- Velocity of solar system wrt CMB frame $\beta \approx 10^{-3}$

- **Coherent Acceleration - $\boldsymbol{\sigma_{\nu N} \propto G_F^2}$**

$a \approx 10^{-13} cm/s^2$ achievable



✓ De Broglie $\lambda \approx 2 - 3$mm

✓ $a_{NR-D} = O\left(10^{-27}\frac{cm}{s^2}\right)$ for non-relativistic Dirac neutrinos

✓ $a_{NR-M} \approx a_{NR-D} \cdot \beta^2 \approx a_{NR-D} \cdot 10^{-6}$

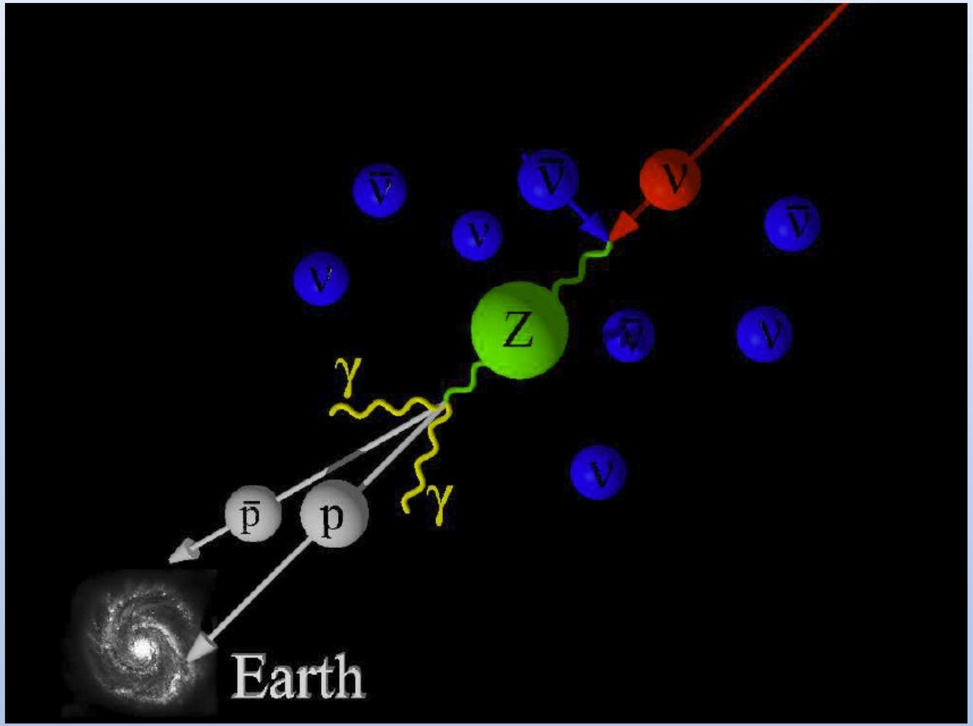
… and worry about solar ν and WIMP backgrounds

arXiv:hep-ph/0107027

3. Cosmic neutrinos

- Interact with high energy ν:

$$E_{\nu_i} \approx 4 \cdot 10^{21} \left(\frac{eV}{m_{\nu_i}} \right) eV$$



- Result:
  1. Dip of high energy ν flux
  2. Excess of high energy γ, proton flux

5. Induced beta decay

PHYSICAL REVIEW VOLUME 128, NUMBER 3 NOVEMBER 1, 1962

Universal Neutrino Degeneracy

STEVEN WEINBERG*
Imperial College of Science and Technology, London, England

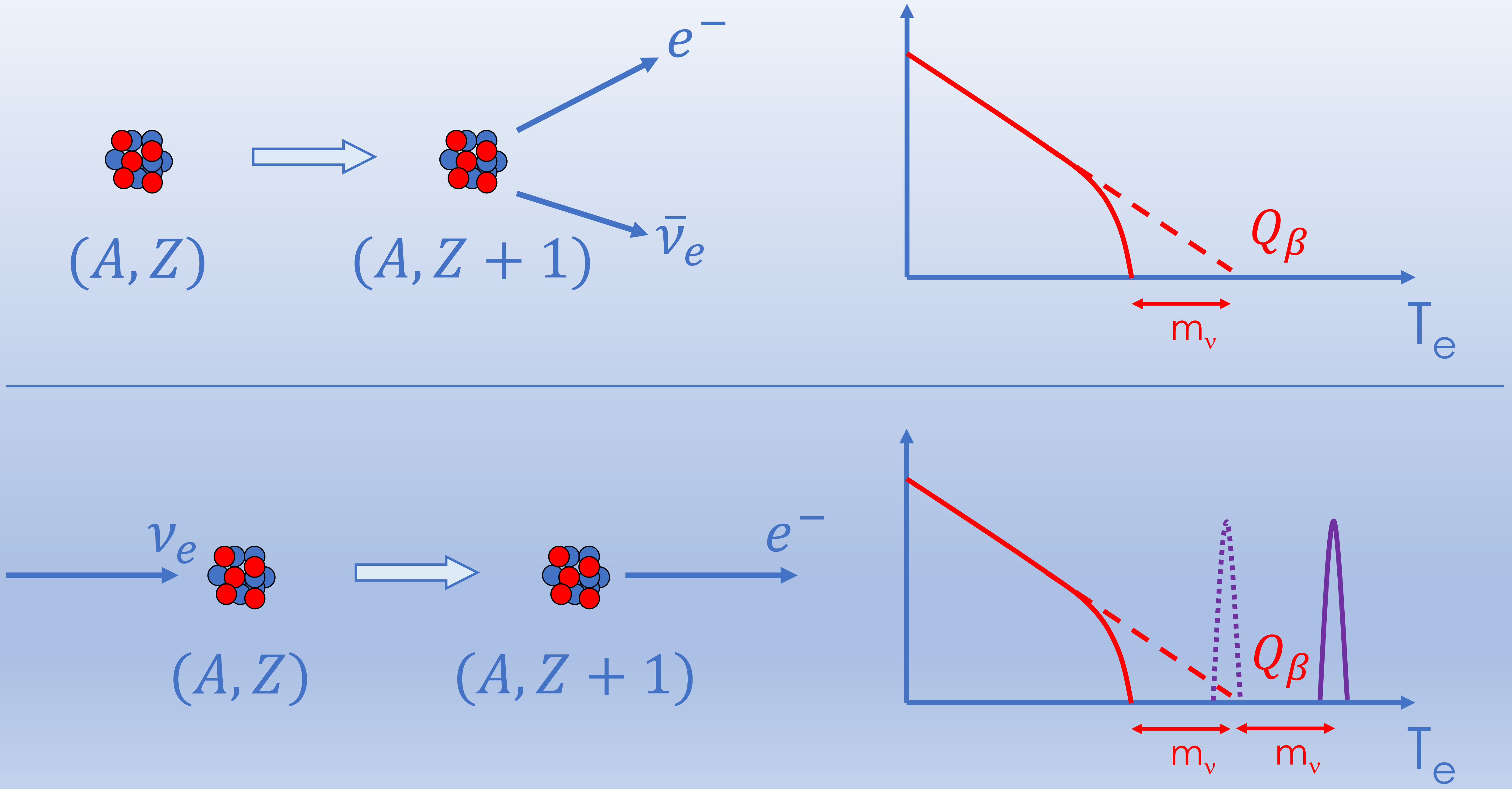
(Received March 22, 1962)

$m_\nu = 0$

Modern cosmological theories imply that the universe is filled with a shallow degenerate Fermi sea of neutrinos. In the steady state and oscillating models (and perhaps also the "big bang" theories) it can be shown rigorously that the proportion of filled neutrino levels (plus the proportion of filled antineutrino levels) is precisely one up to a finite Fermi energy E_F. The proof takes into account both absorption and the repressive effects of already filled levels on neutrino emission. Experiment shows that $E_F \lesssim 200$ eV for antineutrinos and $E_F \lesssim 1000$ eV for neutrinos. The degenerate neutrinos could be observed (if $E_F > 10$ eV) by looking for apparent violations of energy conservation in β^- decay. In the steady state and evolutionary cosmologies E_F is much too low to ever be observed, but in the oscillating cosmologies $E_F \simeq 5R_c$ MeV, where R_c is the minimum radius of the universe in units of its present radius; thus experiment already shows that the universe will contract by a factor over 10^3, if at all. Astronomical evidence plus Einstein's field equation (without cosmological constant) require in an oscillating cosmology that $E_F < 2\times10^{-3}$ eV (so $R_c < 10^{-9}$) and suggest that higher energy neutrinos may represent the bulk of the energy of the universe. A model universe incorporating this idea is constructed.

Cocco, Mangano, Messina calculated $m_\nu \neq 0$ case in 2007

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



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

Selection of target

"Highish" cross-section

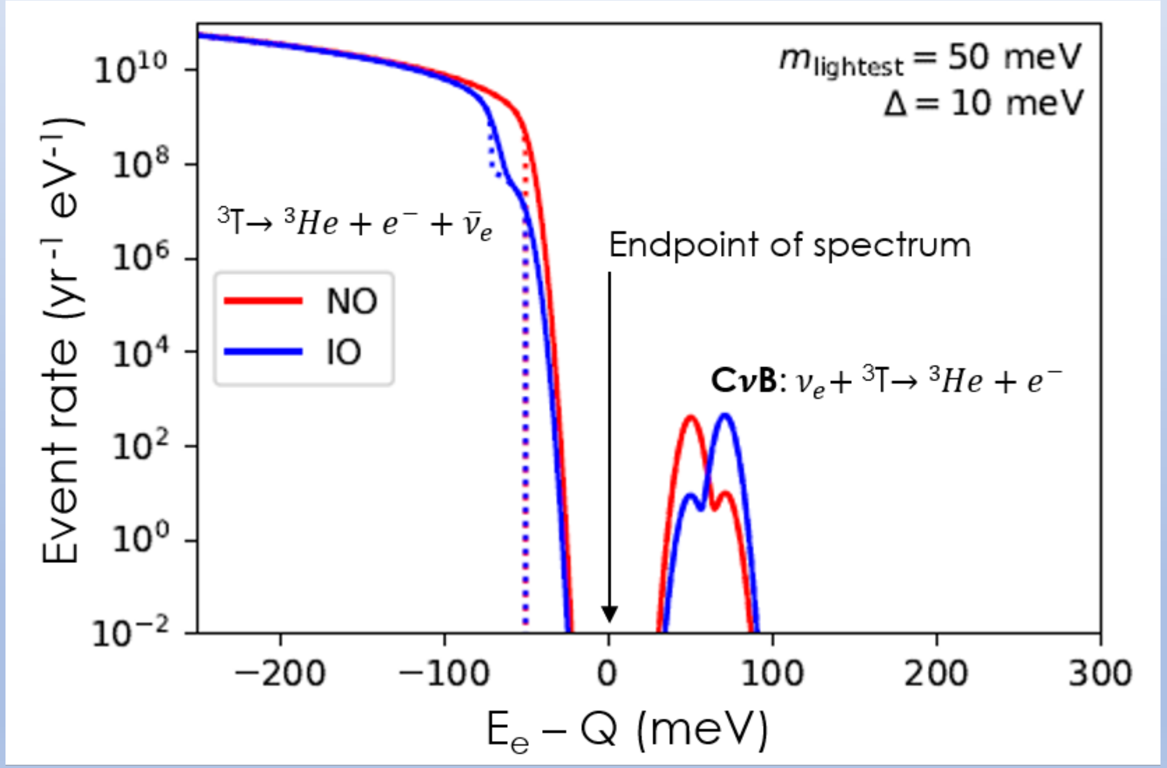
"Longish" lifetime

Isotope	Decay	Q_β (keV)	Half-life (sec)	$\sigma_{\mathrm{NCB}}(v_\nu/c)$ (10^{-41} cm^2)
^{3}H	β^-	18.591	3.8878×10^8	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^9	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^7	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{187}Re	β^-	2.64	1.3727×10^{18}	4.32×10^{-11}
^{11}C	β^+	960.2	1.226×10^3	4.66×10^{-3}
^{13}N	β^+	1198.5	5.99×10^2	5.3×10^{-3}
^{15}O	β^+	1732	1.224×10^2	9.75×10^{-3}
^{18}F	β^+	633.5	6.809×10^3	2.63×10^{-3}
^{22}Na	β^+	545.6	9.07×10^7	3.04×10^{-7}
^{45}Ti	β^+	1040.4	1.307×10^4	3.87×10^{-4}

ν_e → ^3T **Tritium** ^3He → e^-

Tritium

- High cross-section for neutrino capture
- **No energy threshold**
- Sizeable lifetime
- Low Q-value of 18.6 keV
- **Tritium beta decay ~10^{15} Bq/gram**



Expected rate: 100gram-year exposure

Dirac

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

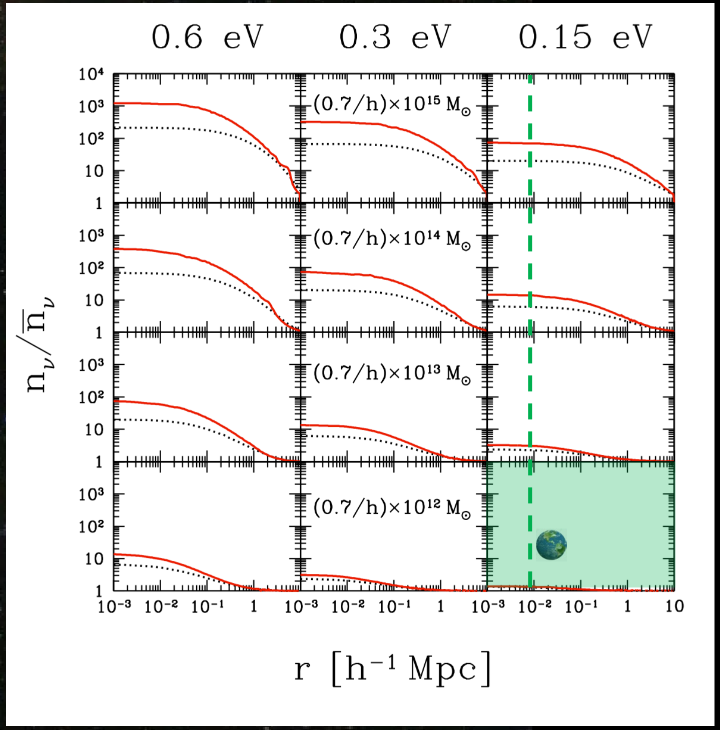
Majorana

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
	x2	x2	x2

https://arxiv.org/abs/hep-ph/0703075
https://arxiv.org/abs/1405.7654

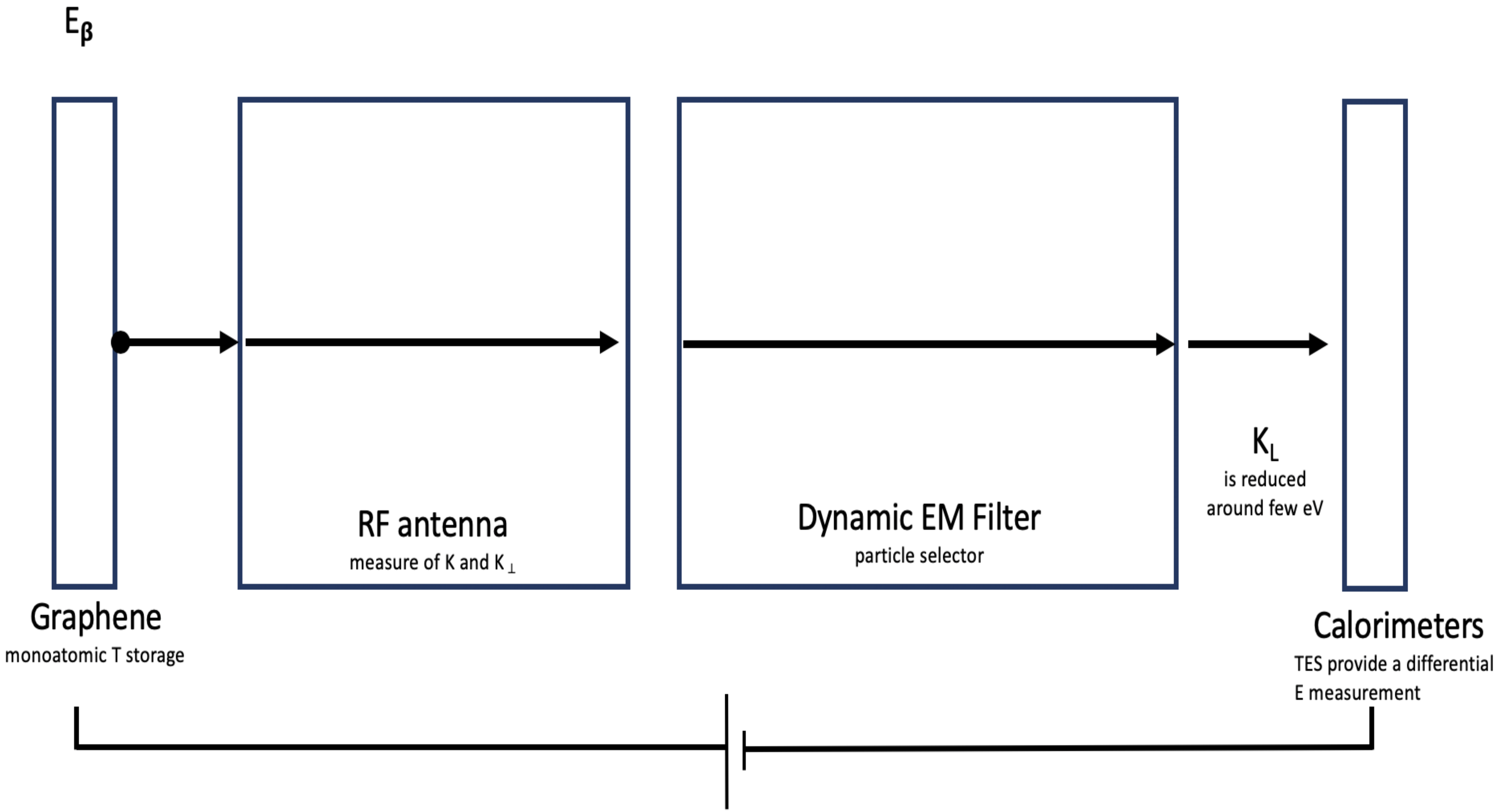
d rate

Gravitational clustering



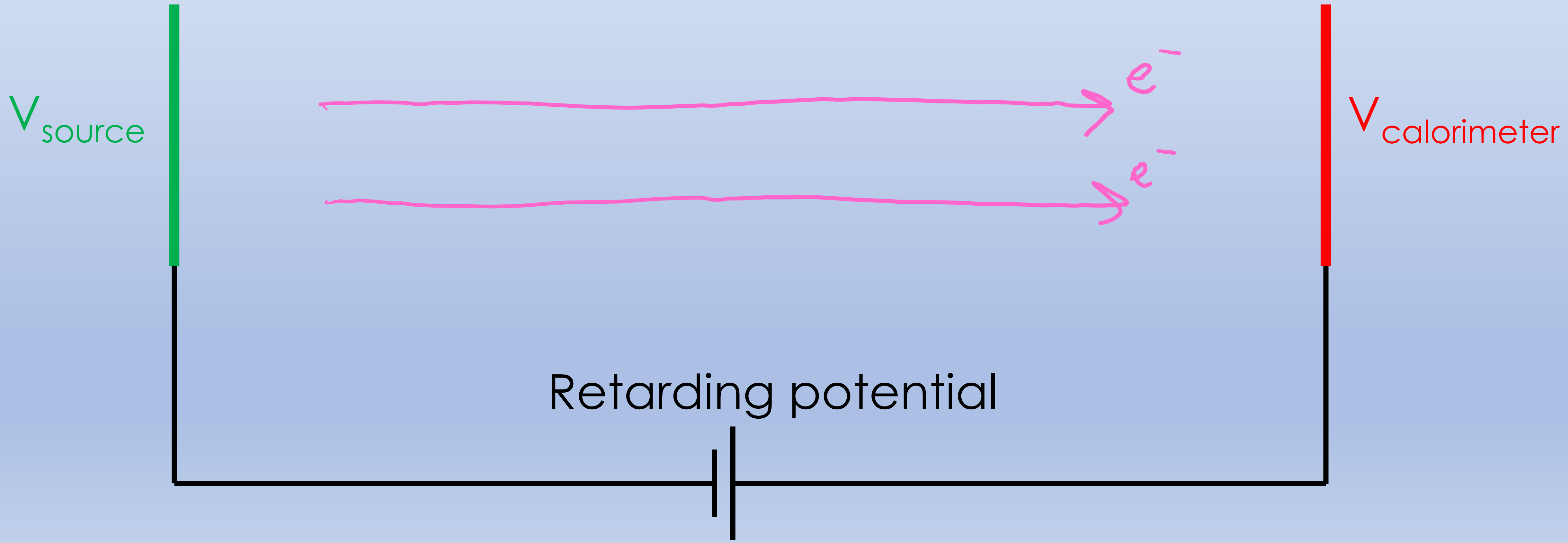
https://arxiv.org/pdf/hep-ph/0408241.pdf

PTOLEMY experiment - concept



PTOLEMY experiment - concept

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



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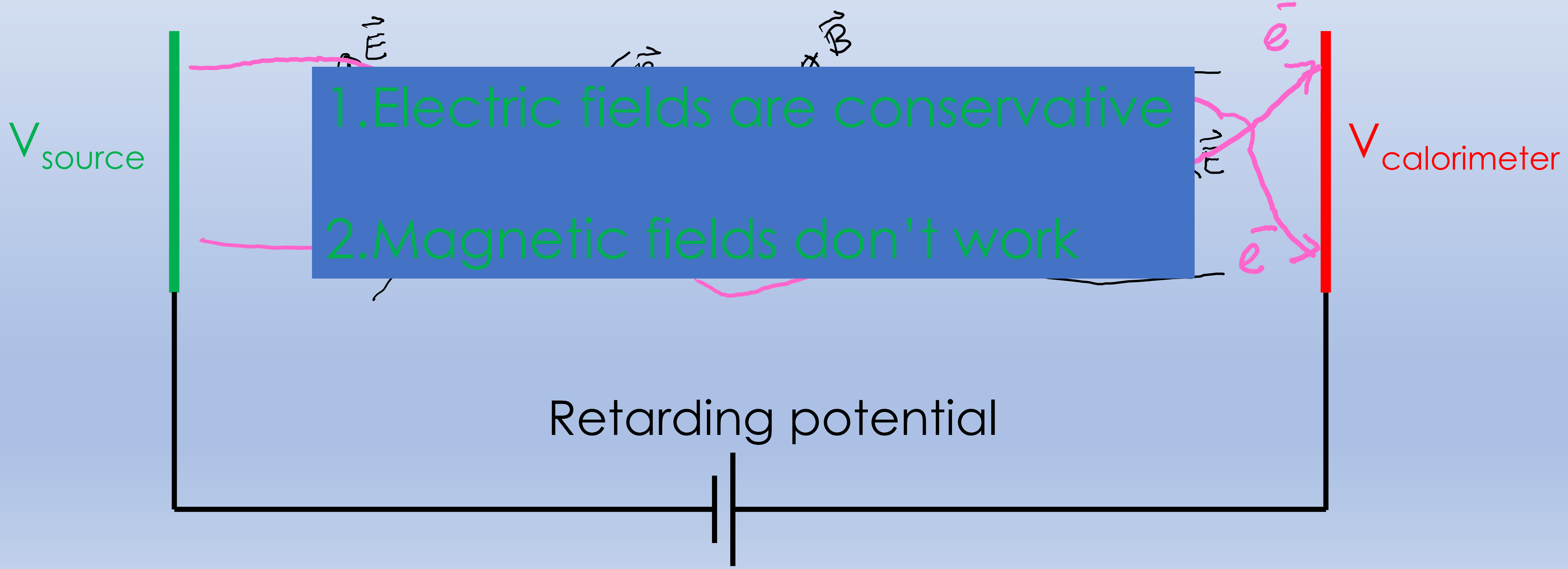
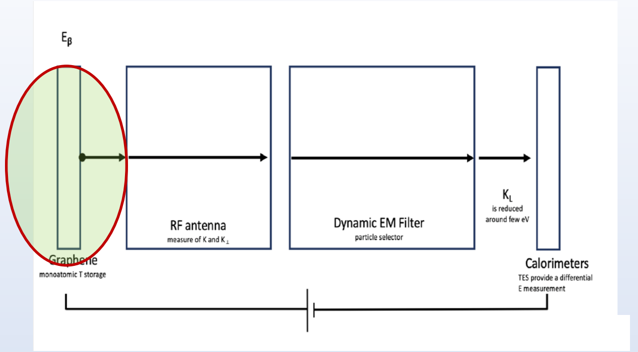


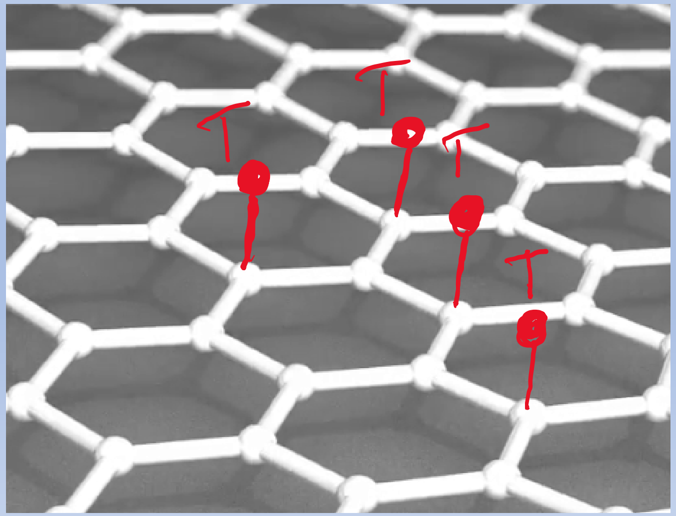
1. Electric fields are conservative
2. Magnetic fields don't work

PTOLEMY: tritium target

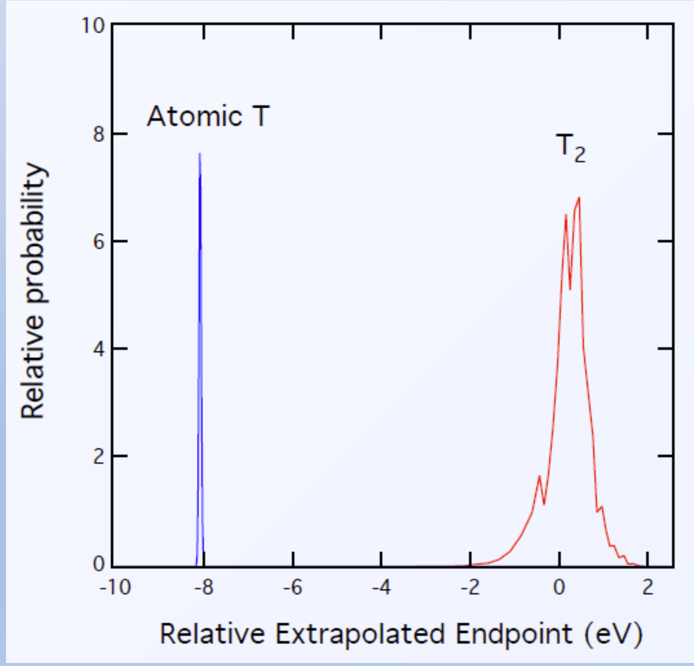


- Use **atomic ^{3}T**
  - No ro-vibrational modes in final state like for ^{3}He-^{3}T final state.
  - Limit to energy resolution not determined by target itself

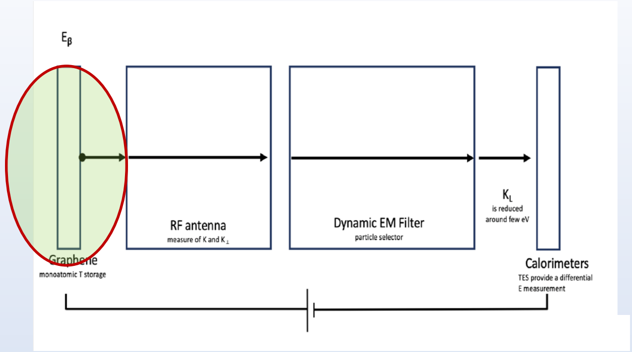
- dE/dx of electrons requires extremely **thin targets**
- We investigate ^{3}T loosely bound to graphene
  - Theoretical maximum is about 0.2 mg tritium per m^2



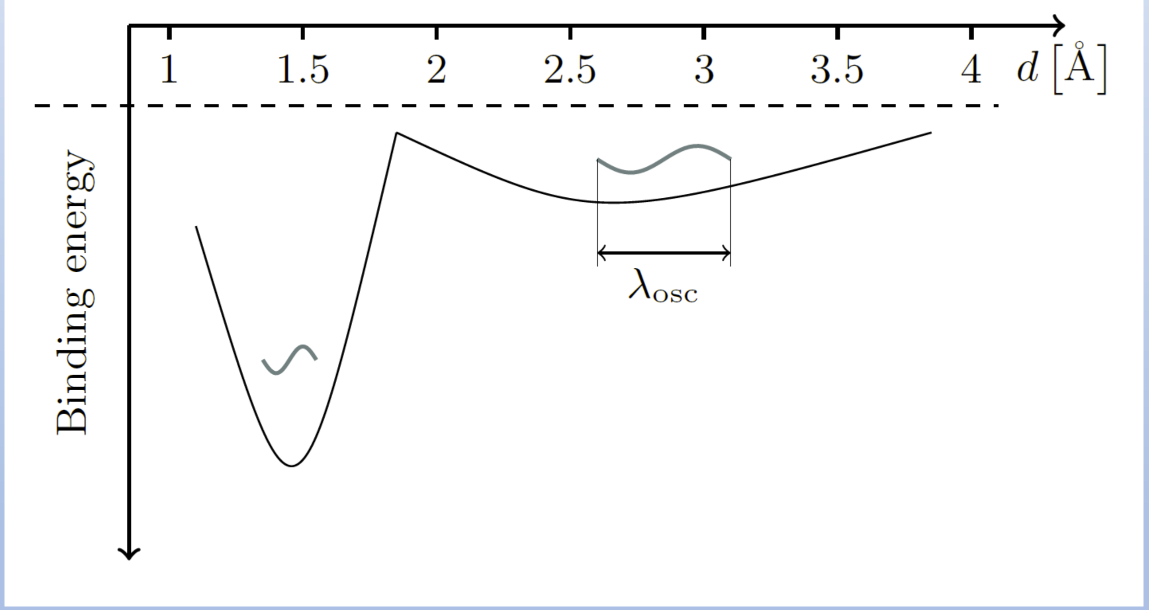
Max 1-tritium for every C



Trouble with Heisenberg?



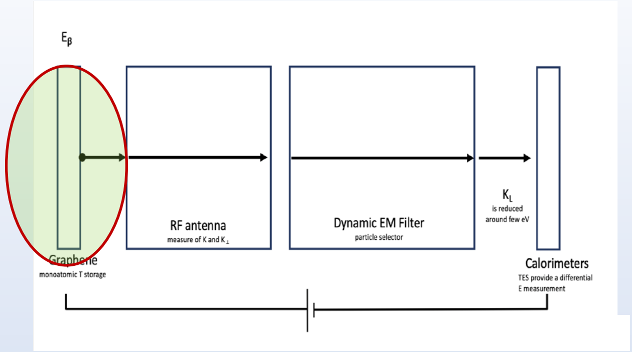
Binding ^{3}T to graphene = localizing ^{3}T → $\Delta p\, \Delta x \geq \frac{\hbar}{2}$ → energy spread



Potential	Source	κ, [eV/Å^2]	λ, [Å]	ΔE, [eV]
Chemisorption	[15]	2.15	0.16	0.60
	[13], GGA	4.62	0.13	0.73
	[13], vdW-DF	4.9	0.13	0.75
Physisorption	[16]	0.08	0.37	0.26
	[15]	0.09	0.34	0.28
	[13], GGA	0.18	0.29	0.33
	[13], vdW-DF	0.13	0.32	0.3
	[14], GGA	0.04	0.43	0.22
	[14], LDA	0.01	0.55	0.17
Migration	[18]	0.283	0.264	0.37

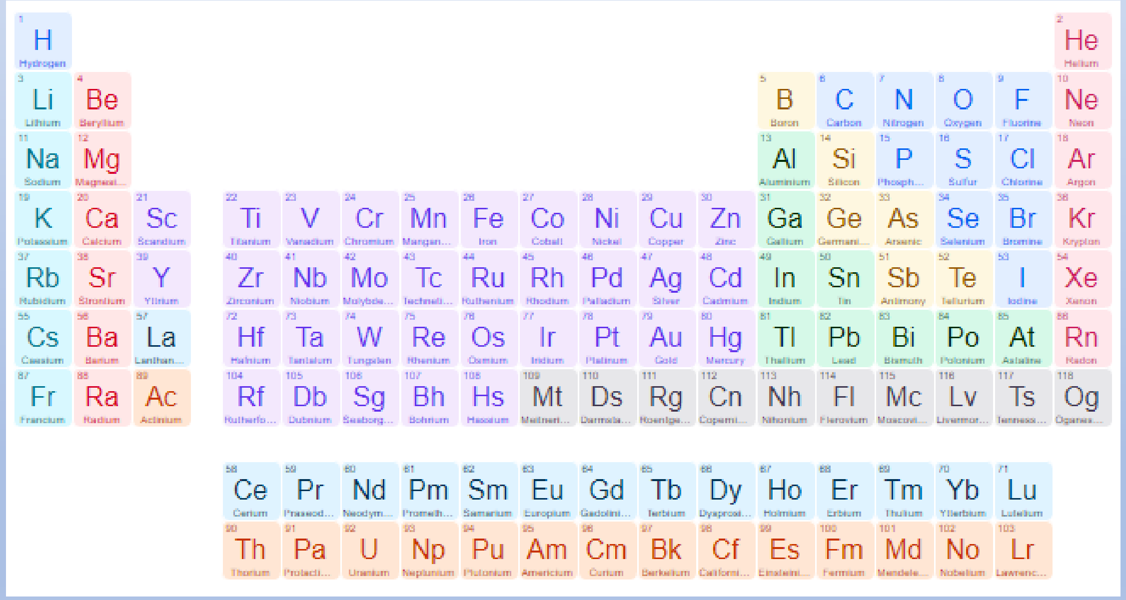
$\Delta E \approx 100 - 400$ meV (?)

Cheipesh et al. https://arxiv.org/abs/2101.10069v2



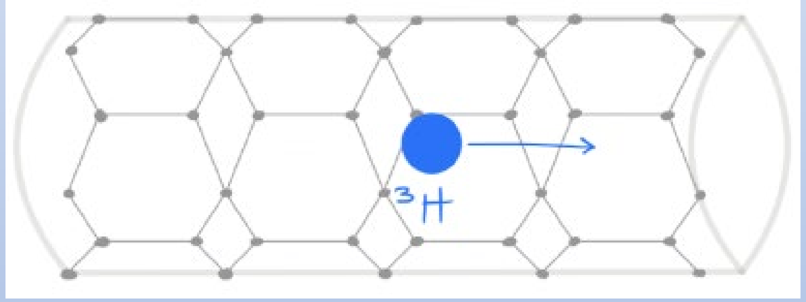
Ways to solve?

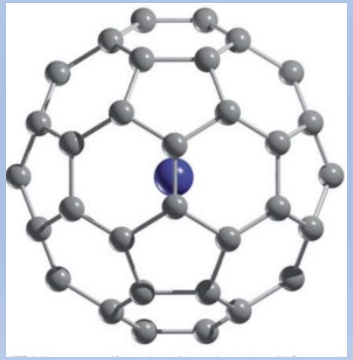
Strategy 1: find other target material



from Mendeleyev et al

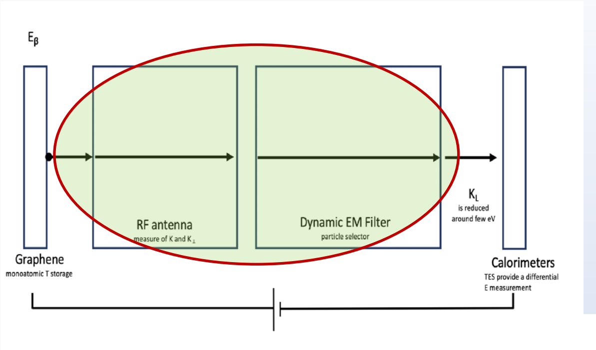
Strategy 2: alternative ^{3}H storage



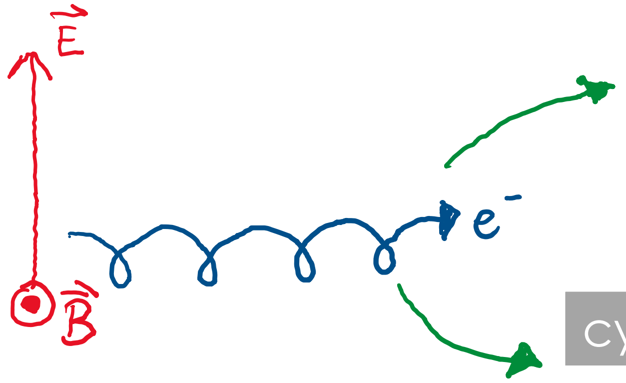


from A. Esposito

PTOLEMY: two types of drift



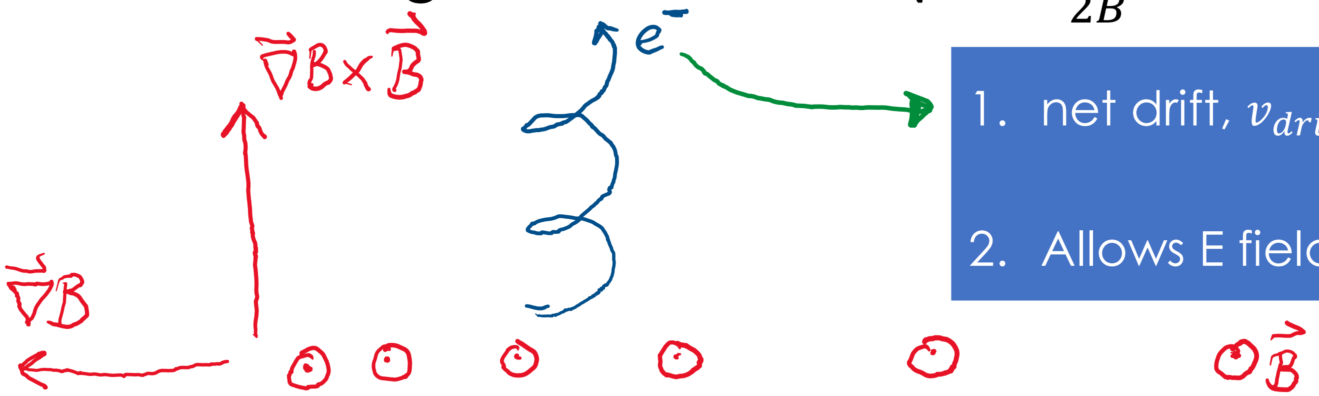
I: $\vec{E} \times \vec{B}$ drift



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

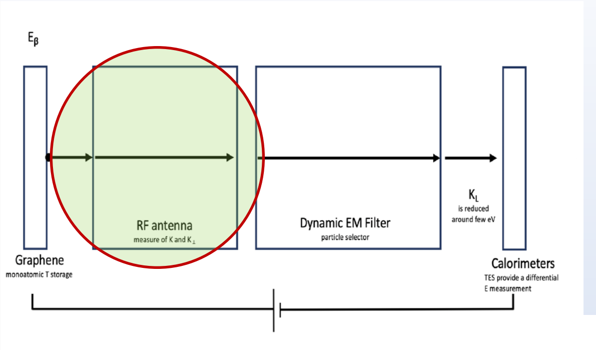
cyclotron motion – detectable RF

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

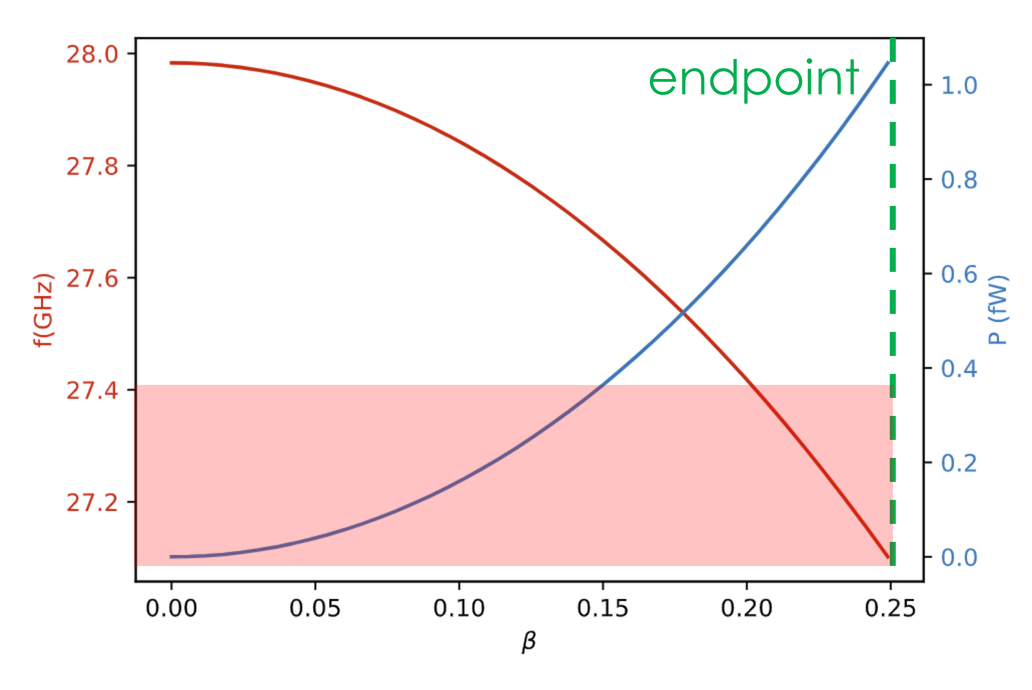


1. net drift, $v_{drift} = \mu \frac{|\vec{\nabla} B|}{B}$
2. Allows E field to work (!): $\frac{dT_\perp}{dt} = e\vec{E} \cdot \vec{v}_{drift}$

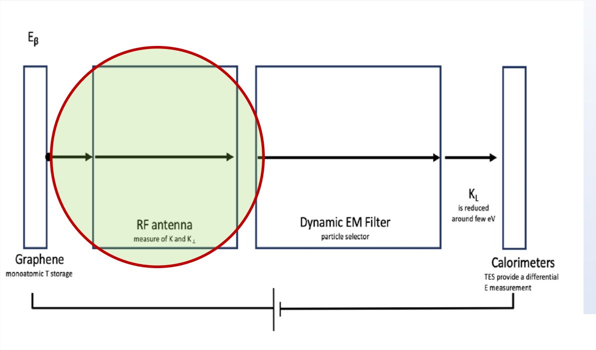
PTOLEMY: RF pickup



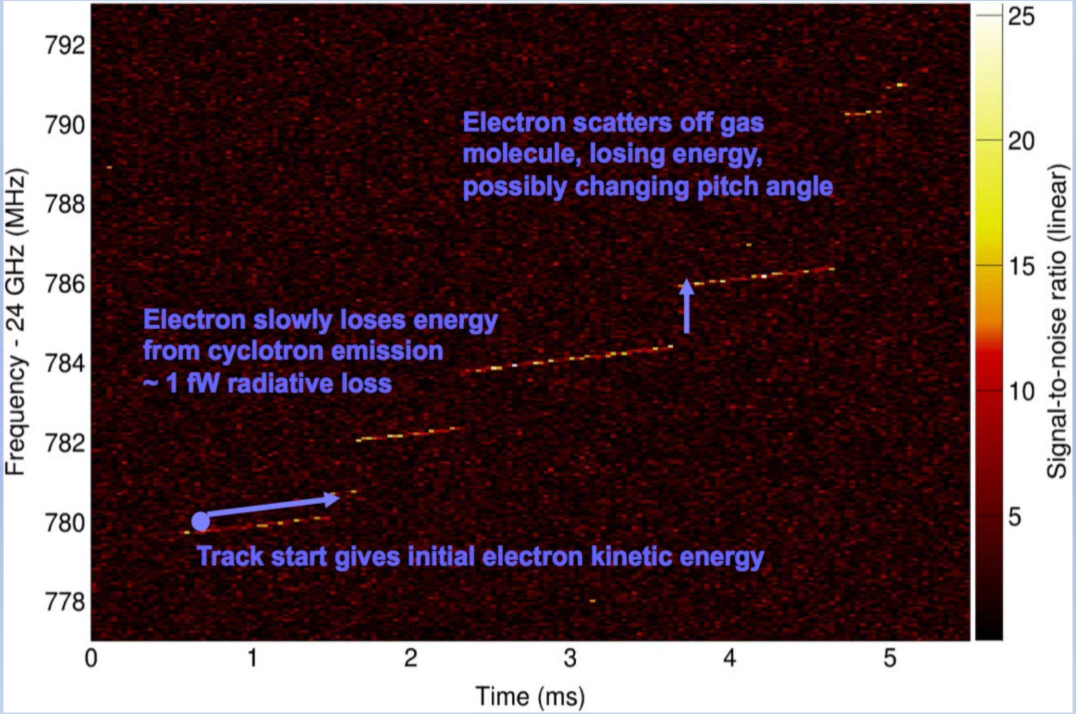
- Transport electrons through **ExB** field
- RF emission with $f = \frac{1}{2\pi}\frac{eB}{m_e\gamma} \approx 27GHz$
- Power $P = \frac{1}{4\pi\epsilon_0}\frac{2e^4B^2}{3m_e^2c}(\gamma^2 - 1)\sin^2\theta \approx 1\,fW \rightarrow \theta$ is angle between B and $\vec{\beta}$

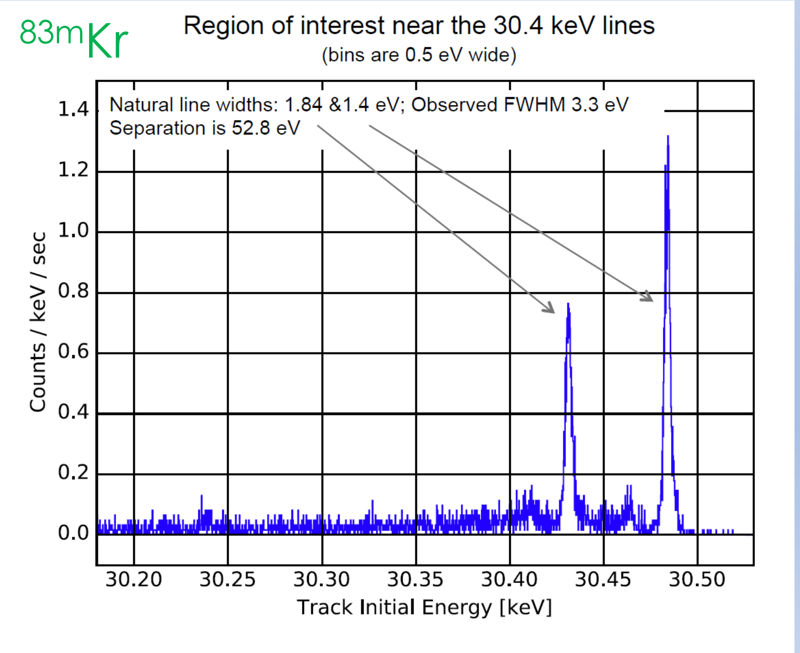


PTOLEMY: RF pickup



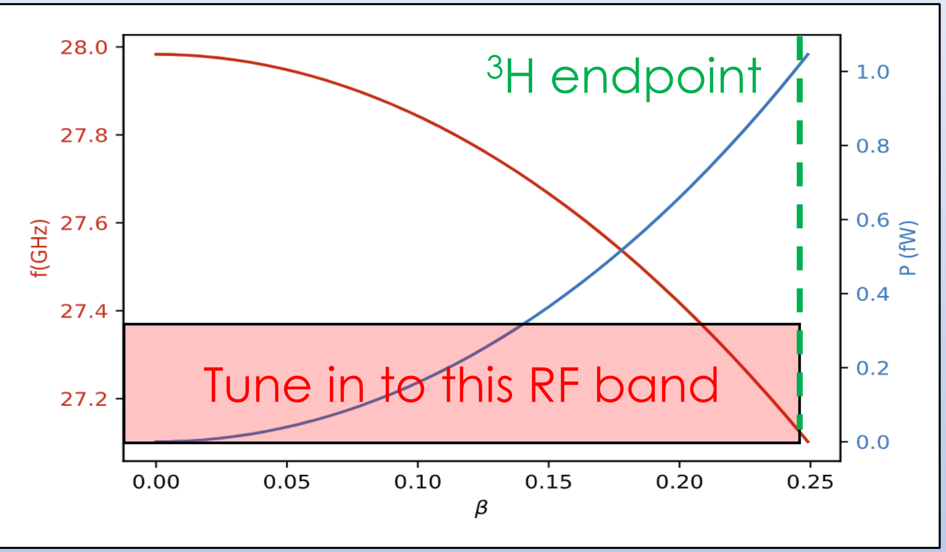
- Transport electrons through **ExB** field
- RF emission with $f = \frac{1}{2\pi}\frac{eB}{m_e\,\gamma} \approx 27GHz \rightarrow \gamma =$ Energy
- Power $P = \frac{1}{4\,\pi\epsilon_0}\frac{2\,e^4B^2}{3m_e^2c}(\gamma^2 - 1)\sin^2\theta \approx 1\,fW \rightarrow \theta$ is angle between B and $\vec{\beta}$

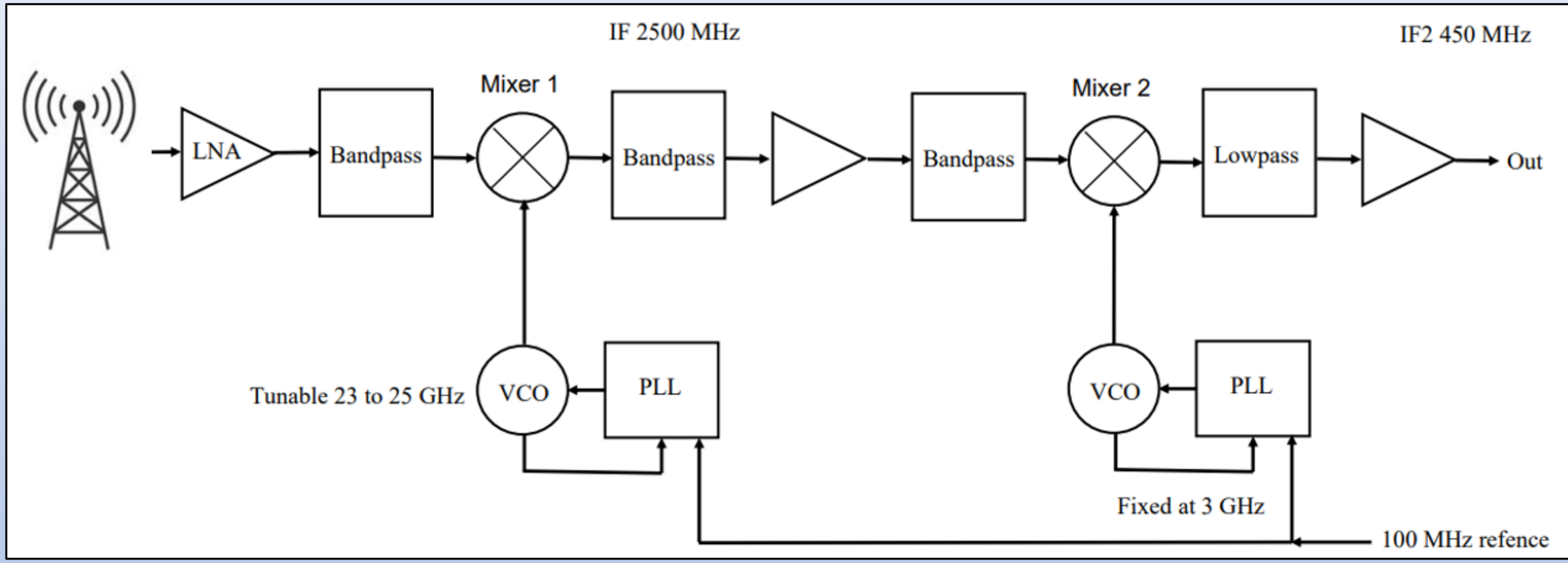


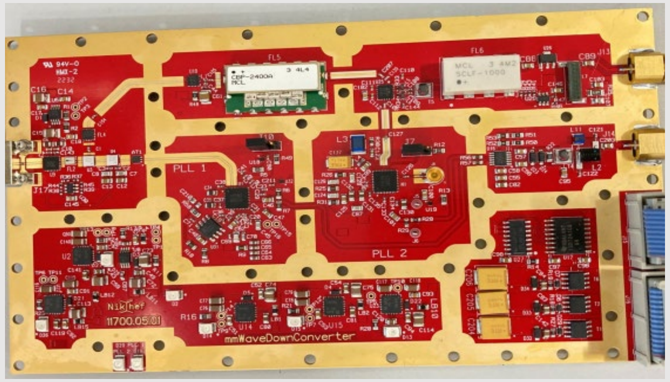


Pioneering work by Project8 @ FNAL
A.Esfahani et. al, JPG Vol44,#5, 2017
https://arxiv.org/abs/1703.02037v1

PTOLEMY: RF pickup @ Nikhef

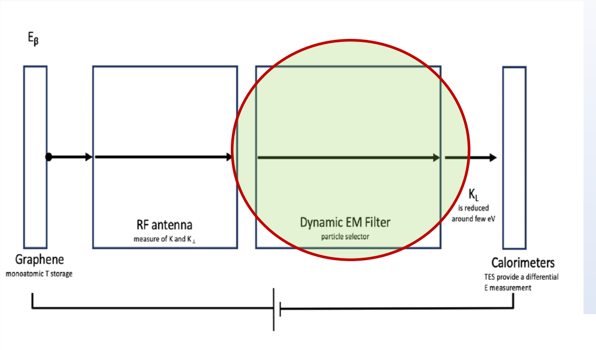


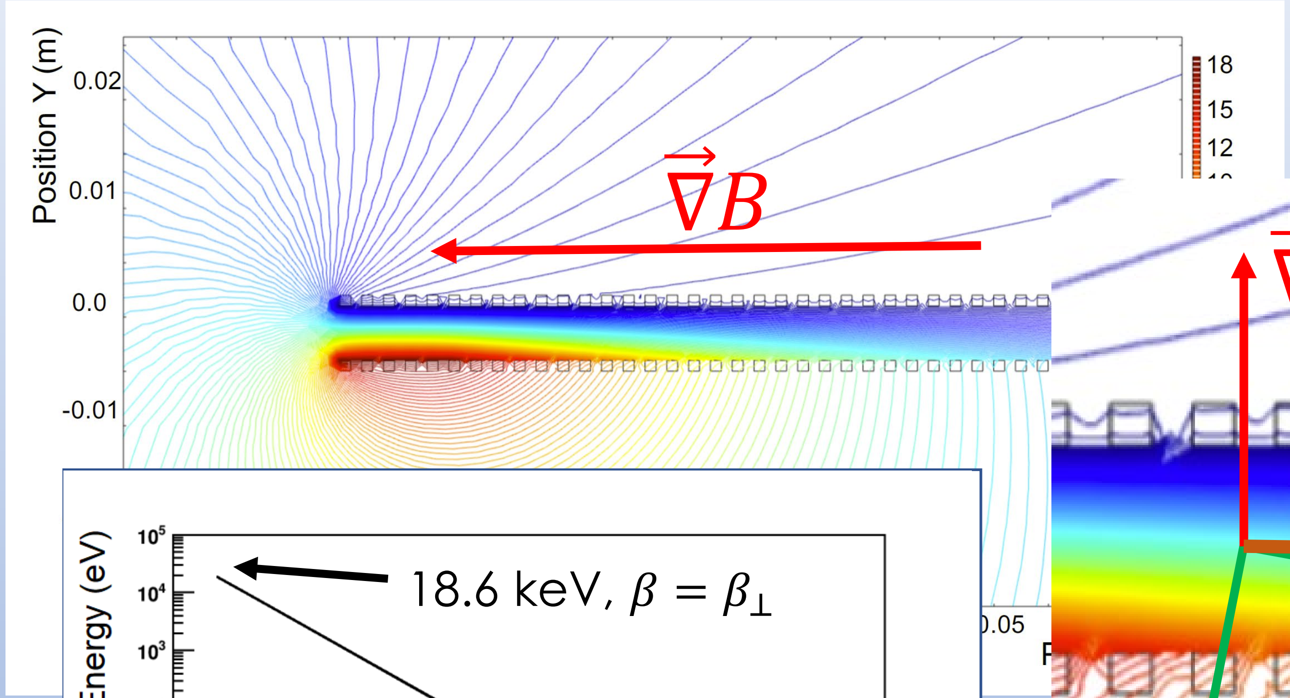


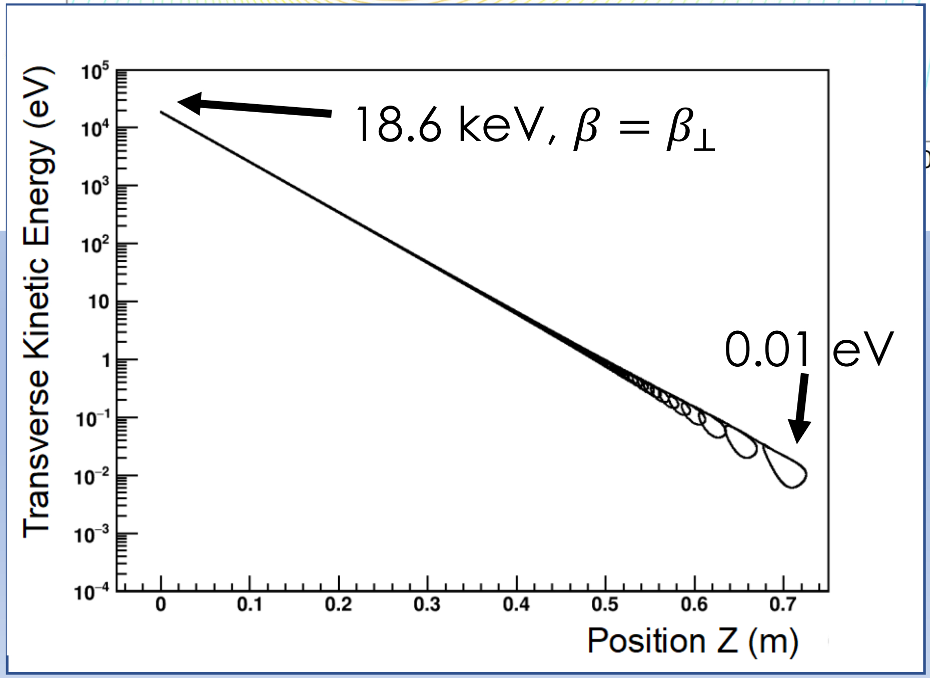


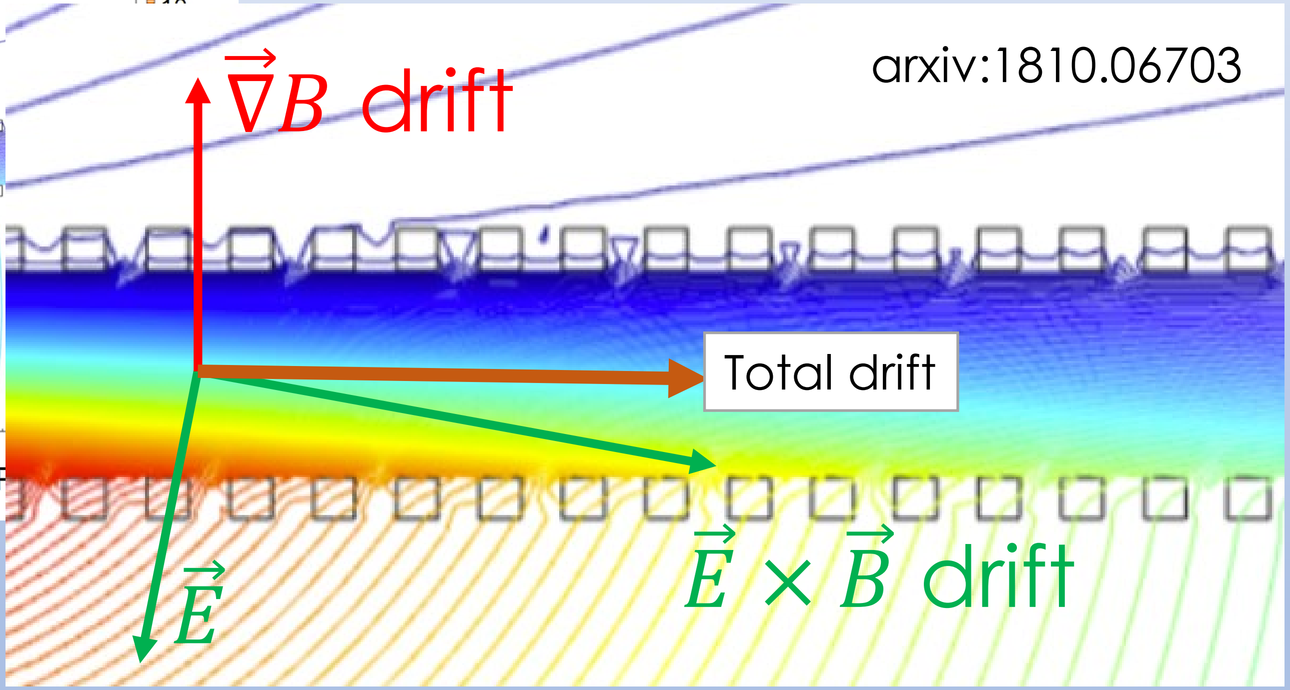
Trigger
HV

PTOLEMY: Transverse drift filter





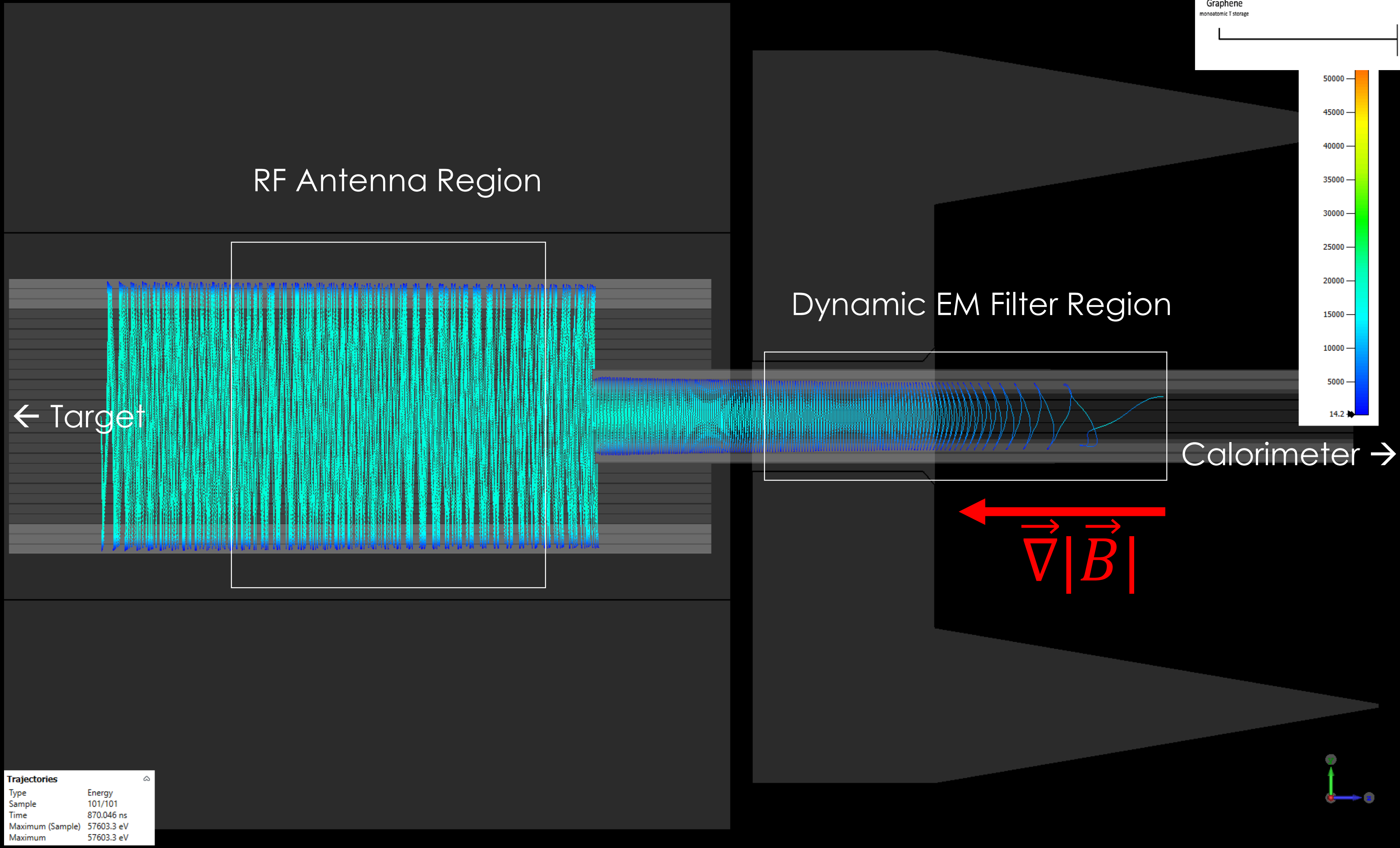


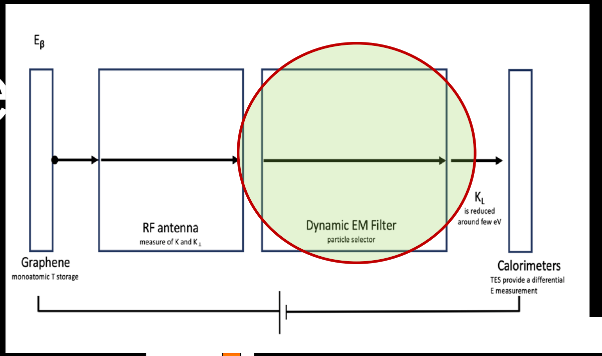


After filter, only component of β parallel to B is left.

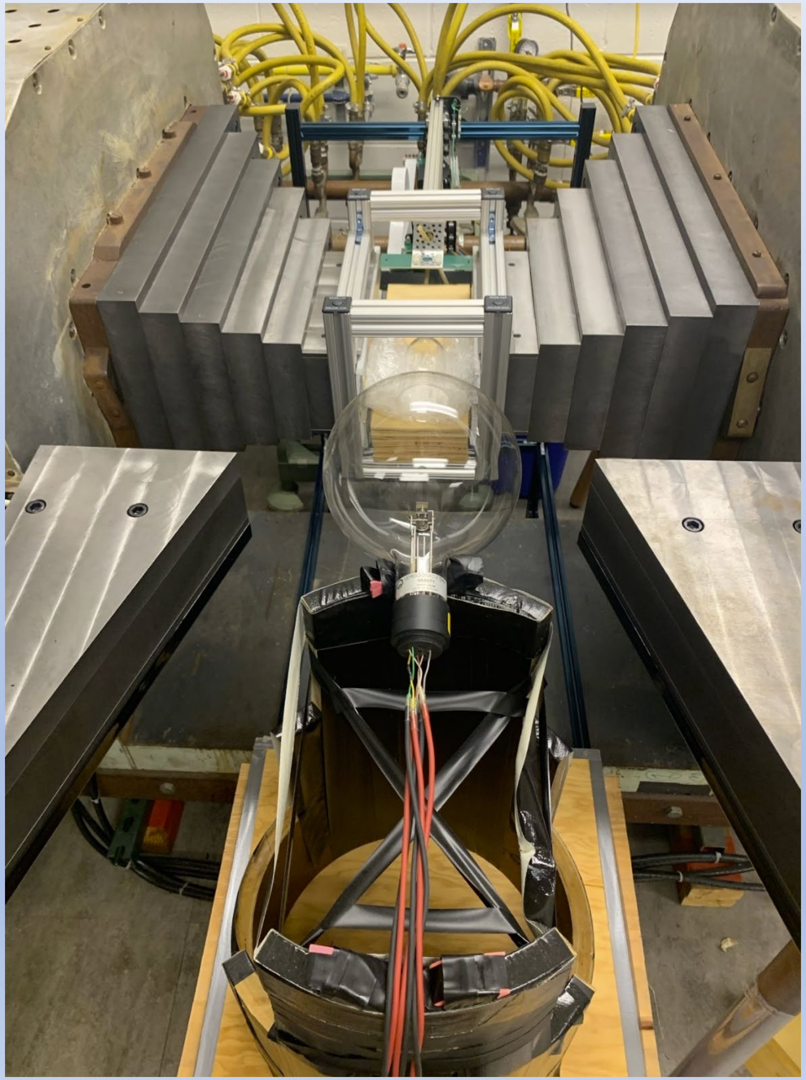
Can be reduced by retarding potential

Electron Transport: RF pickup & Filte

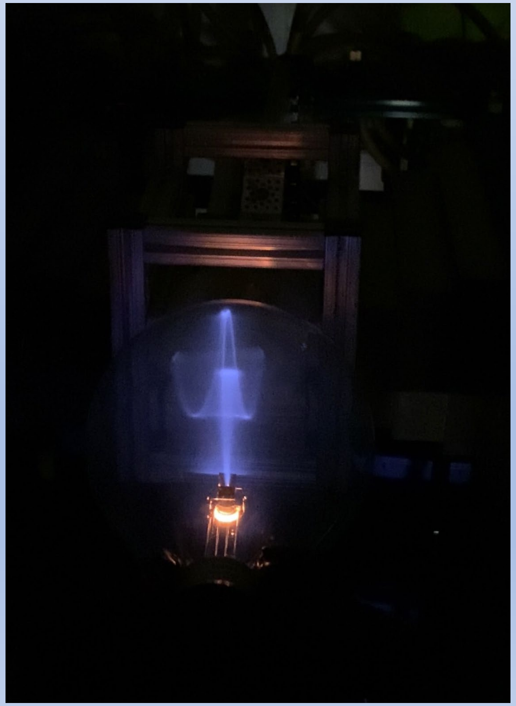




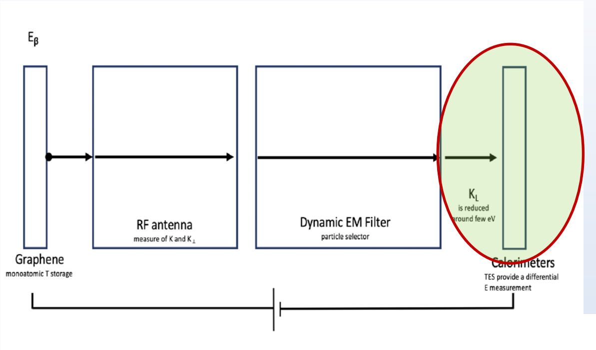
PTOLEMY: RF + transverse drift filter



- US – Italian – Dutch enterprise to make demonstrator setup
- Expect ‘something’ under construction at LNGS in 2023



PTOLEMY: Energy



- Energy measurement from ΔV and calorimeter:

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

- Calorimeter energy resolution must be O(50meV)
  1. Transition Edge Sensors
  2. State-of-the-art 202x O(100meV@100eV)

- Voltage stability over experiment better than 10-20mV

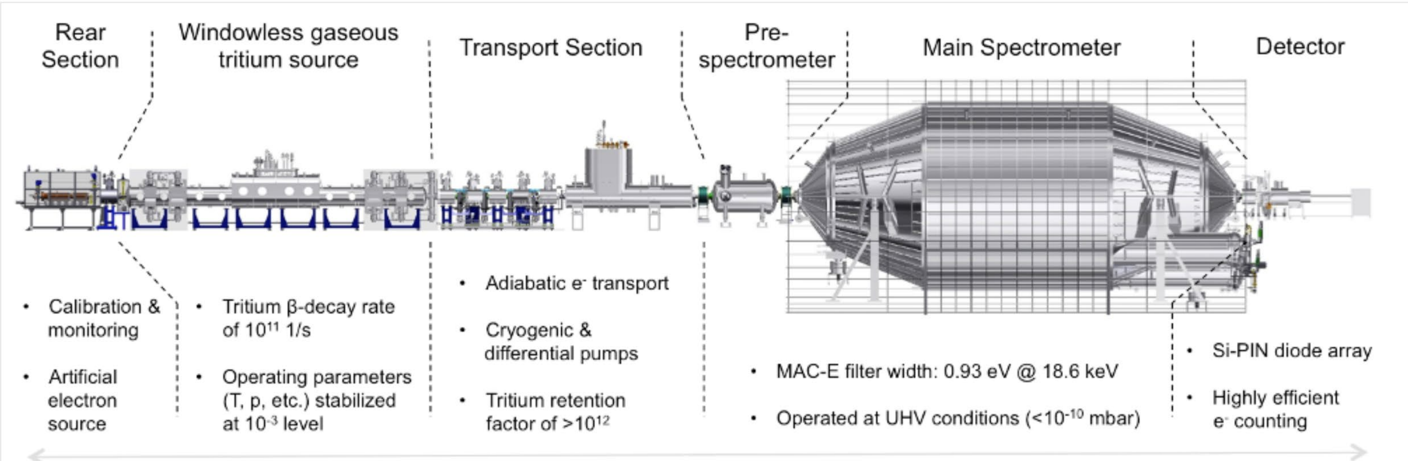
- NOTE: internal voltages are actively adjusted for each interesting electron

PTOLEMY: "expected" performance

1. Sensitivity to m_ν
2. Sensitivity to $C\nu B$
3. Astronomy with $C\nu B$

PLEASE NOTE

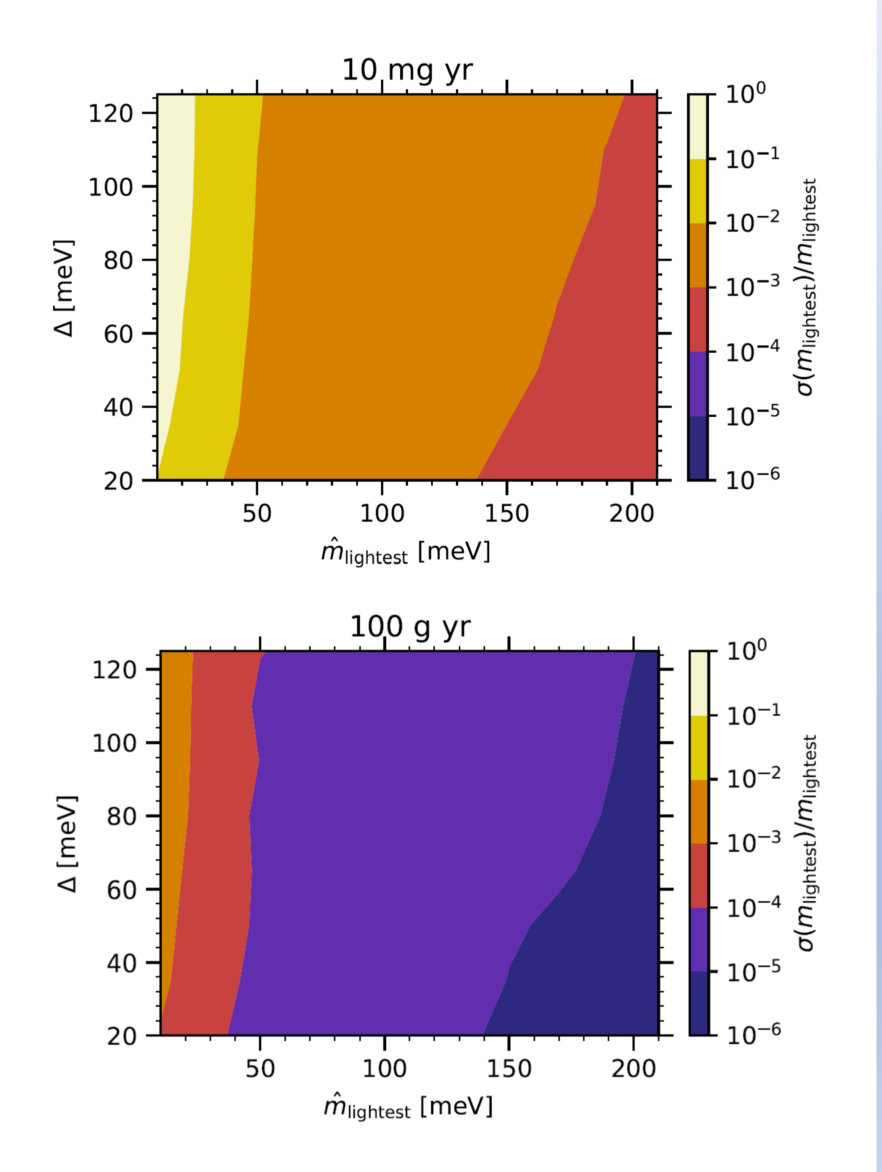
KATRIN = experiment with street credibility



https://www.katrin.kit.edu/

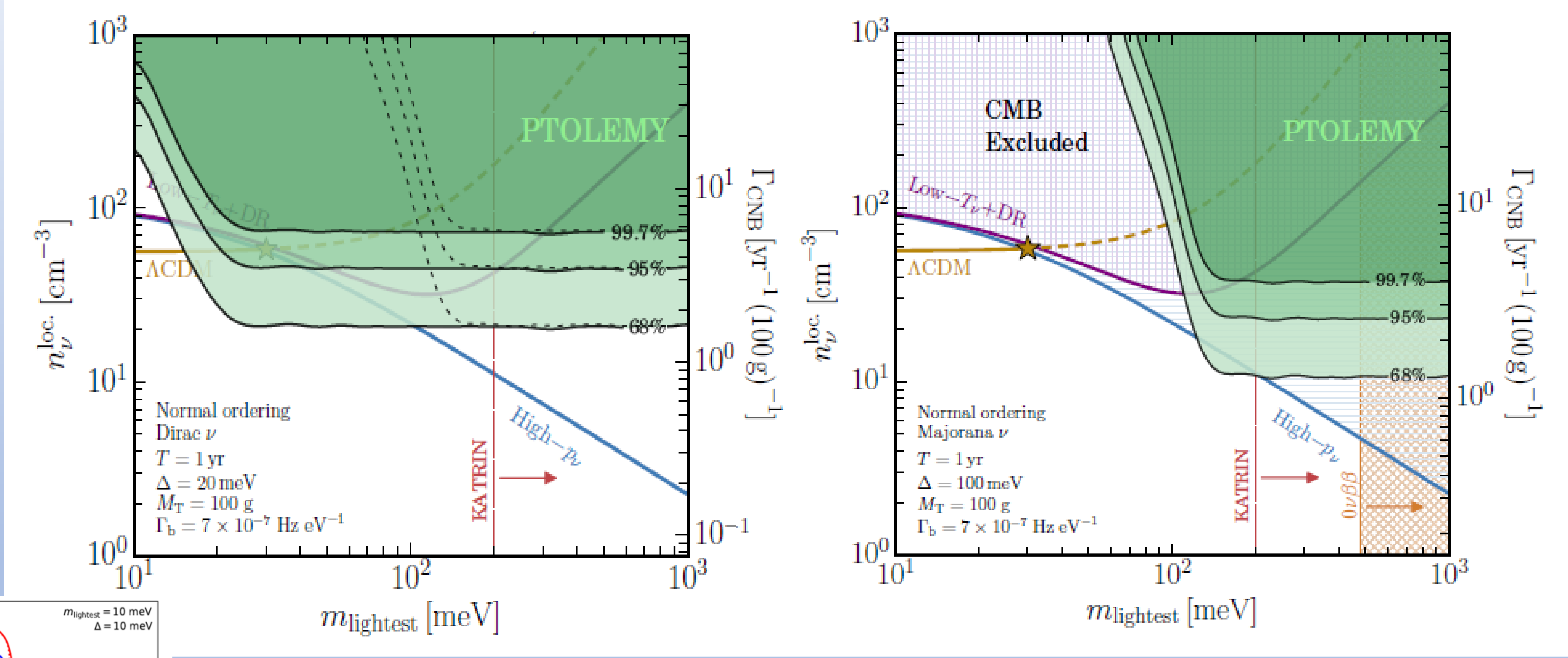
PTOLEMY: m_ν "expected" performance

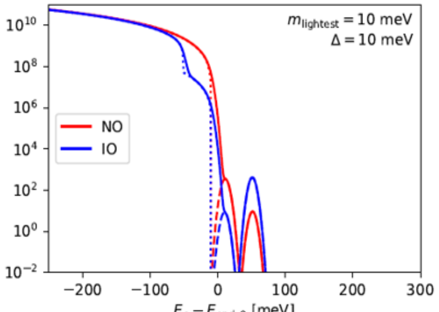
- Neutrino mass as first result
  1. Small exposure already gives sensitivity to O(10meV) m_ν
  2. Crucial for design of full scale $C\nu B$ PTOLEMY with 100g tritium
- Mass hierarchy
  1. Clearly decided with 100g yr exposure
  2. Up to masses <100meV



arxiv:1902.05508

PTOLEMY: $C\nu B$ expected performance





https://arxiv.org/abs/2111.14870

science fiction noun

Save Word

Definition of *science fiction*

: fiction dealing principally with the impact of actual or imagined science on society or individuals or having a scientific factor as an essential orienting component

$C\nu$B : Astronomy (SF)

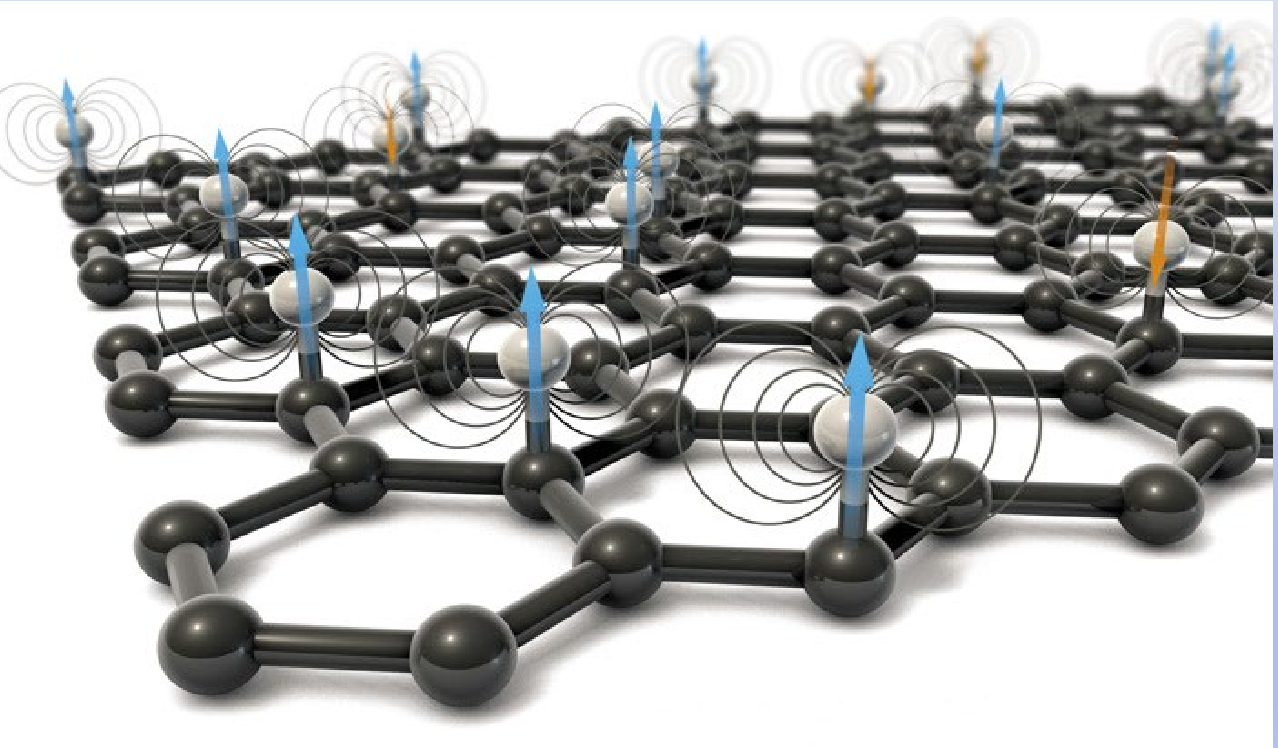
1. Suppose you have discovered $C\nu B$
2. Suppose you have a polarized target

1+2. Localization of neutrinos:

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \cos\theta$$

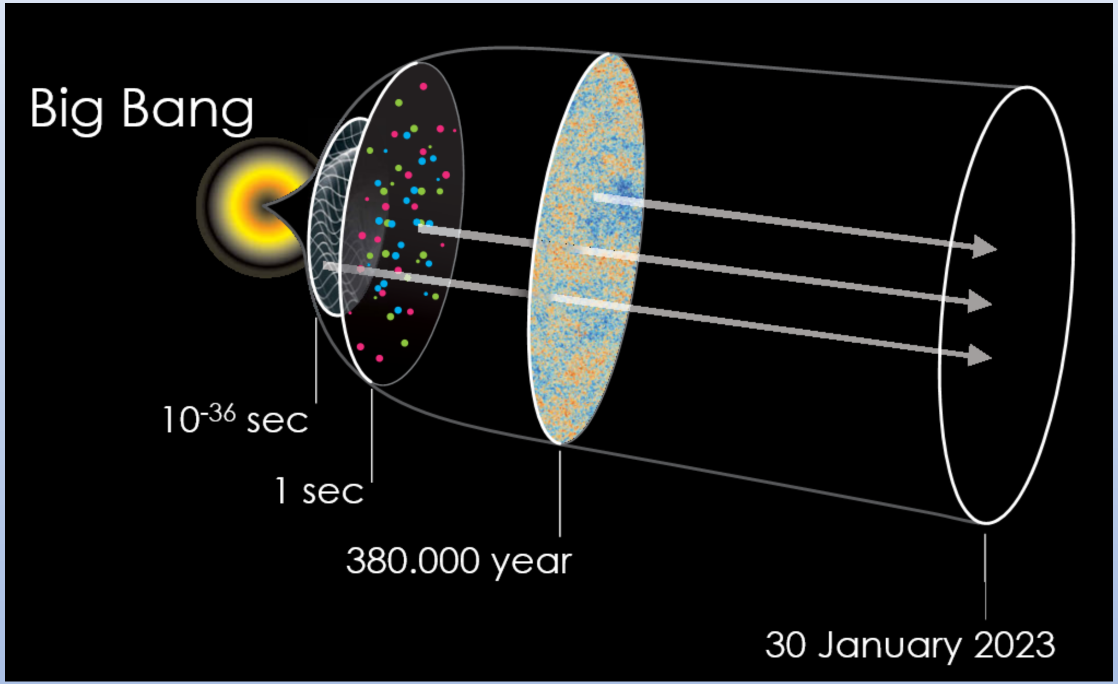
Why interesting?

Graphene with polarized tritium nuclear spin



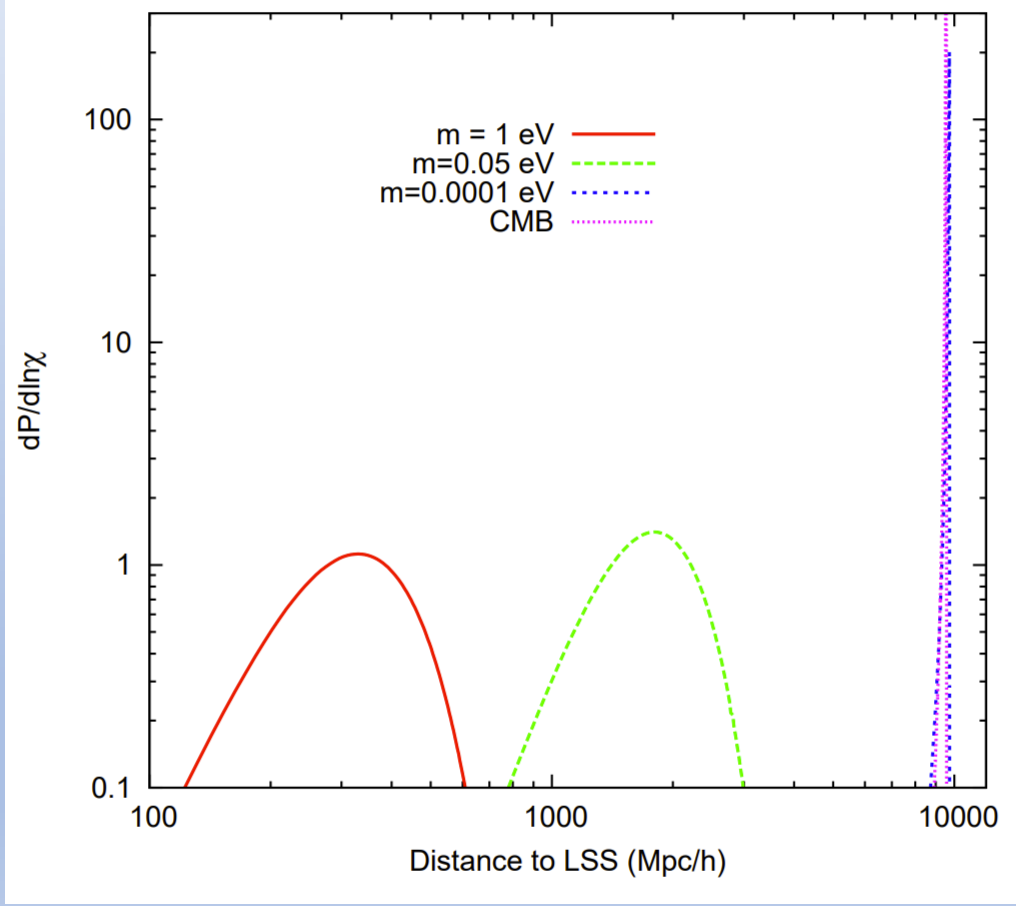
$C\nu B$: Astronomy

Big Bang in "time"



1. $C\nu B$ has large non-relativistic component
2. It comes from '**nearby**' compared to CMB

Big Bang in "distance"

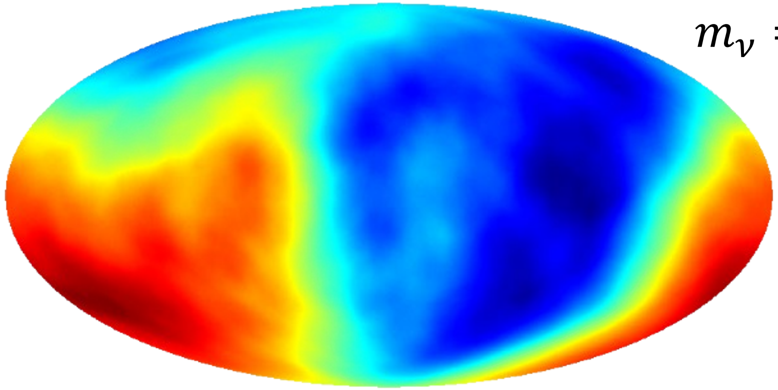


Phys. Rev. Lett. **103**, 249901 (2009)

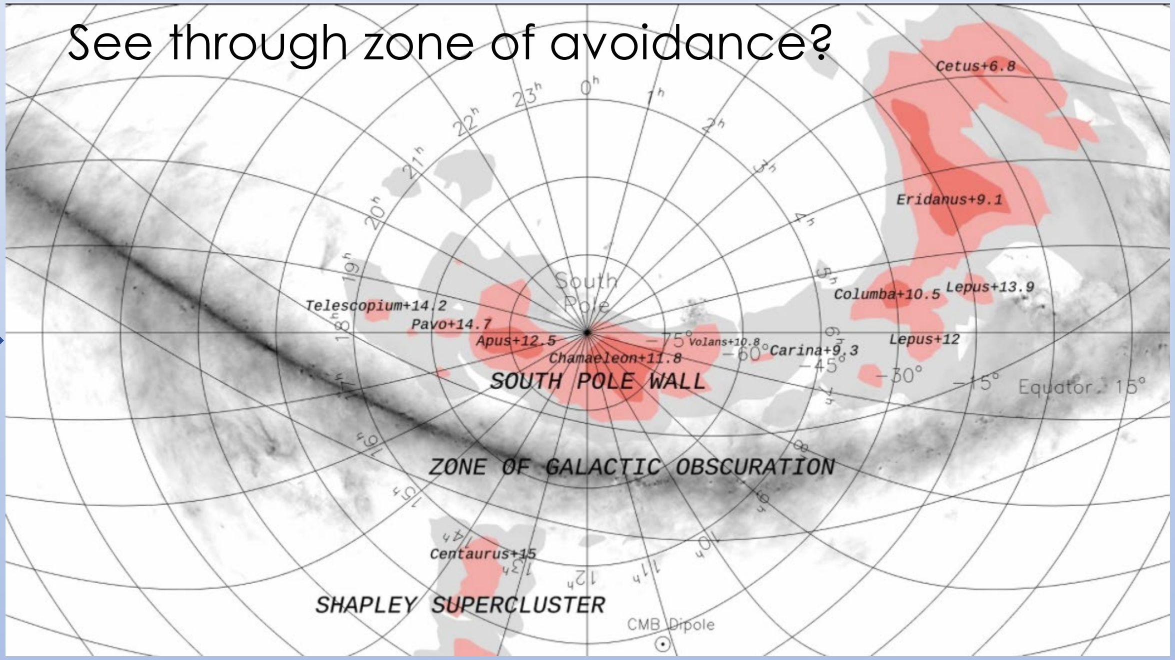
$C\nu B$: Astronomy

1. Neutrinos ‘feel’ large scale structure at distances of O(5Gly)
2. Fluctuations hugely amplified because ν non-relativistic → $1/v^2$
3. Maybe even O(1-10%)

$m_\nu = 0.01eV$



See through zone of avoidance?



Could be connected to optical sky surveys….

Multi-messenger astroparticle physics?