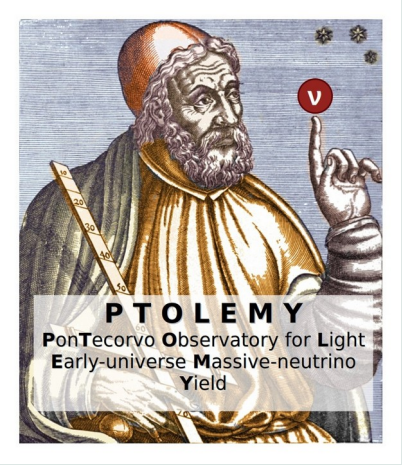
Status of the Ptolemy project



Nicola Rossi

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Istituto Nazionale di Fisica Nucleare

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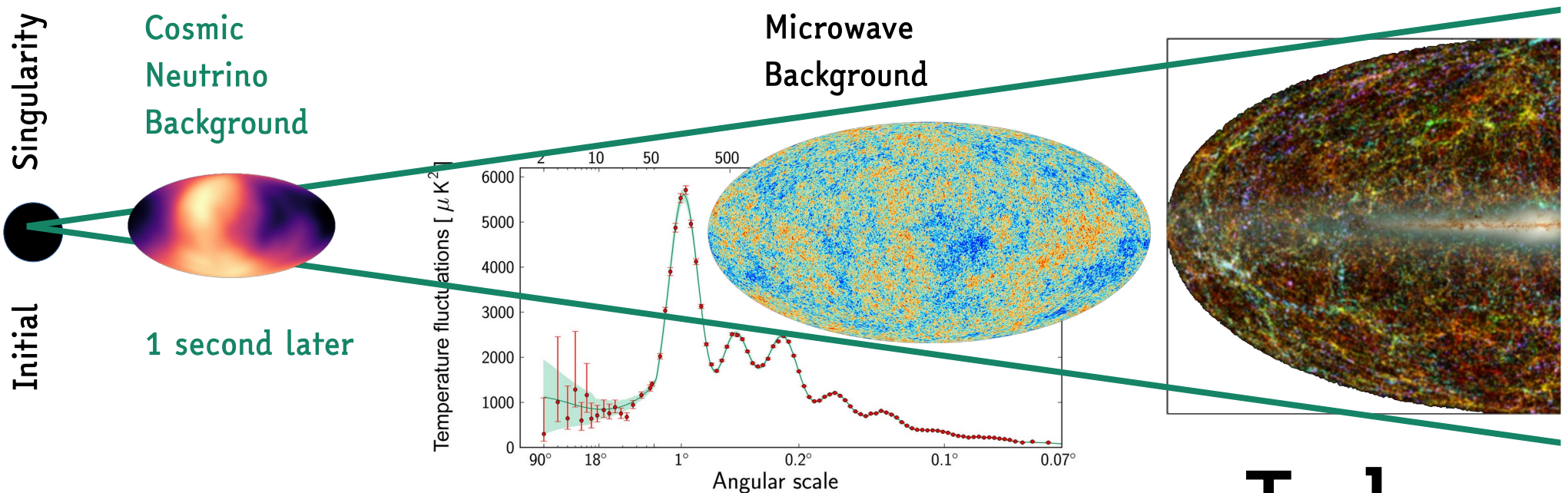
On behalf of the Ptolemy Collaboration

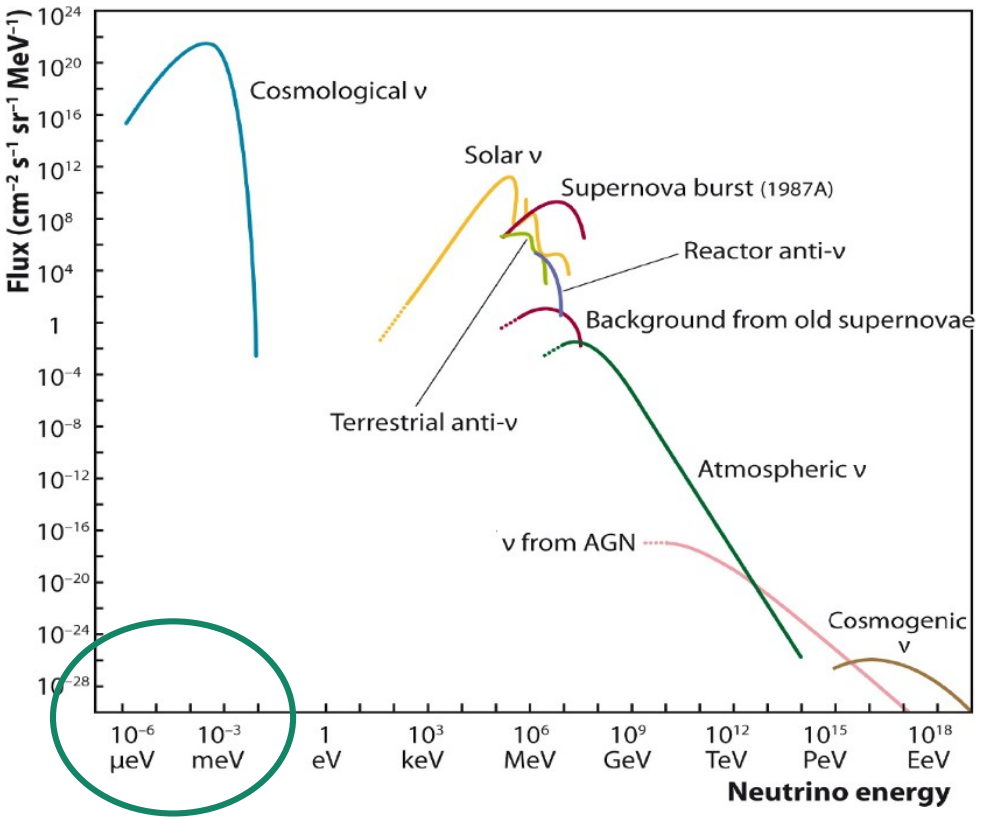
TAUP 2025, Xichang (China)

18-23 August 2025

Cosmic Neutrino Background



The most abundant neutrino flux



$$T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma \simeq 1.95\,\mathrm{K}$$

$$\rho_\nu \simeq 300\ \mathrm{cm}^{-3}$$

$$\Sigma_i m_i \lesssim 250\ \mathrm{meV}$$

$$\Omega_\nu / \Omega_b \simeq 0.12$$

Detection Principle

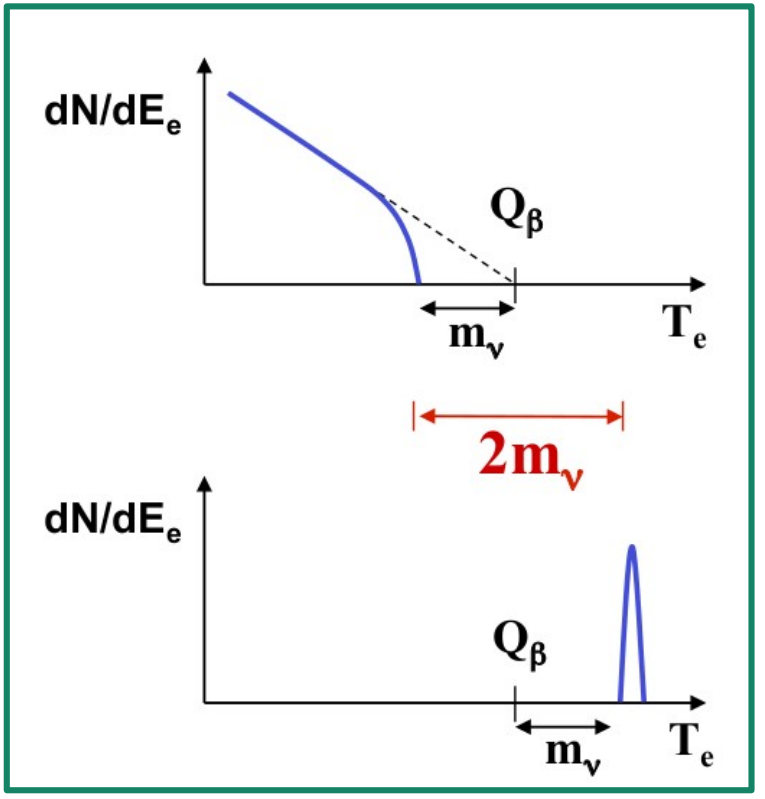
Weinberg, 1962 → Cocco, Mangano & Messina, 2007

★ Threshold-less

$$\nu_e + (A, Z) \rightarrow (A, Z+1) + e^-$$

★ Monochromatic peak at Q+m

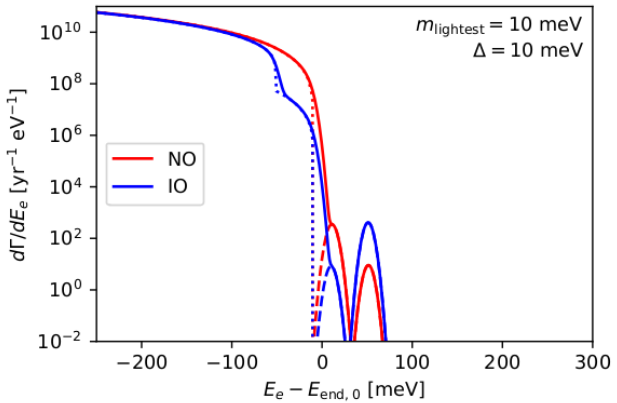
★ Neutrino mass as by-product

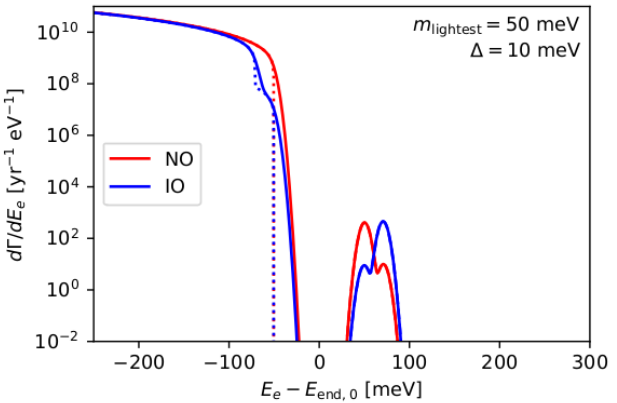


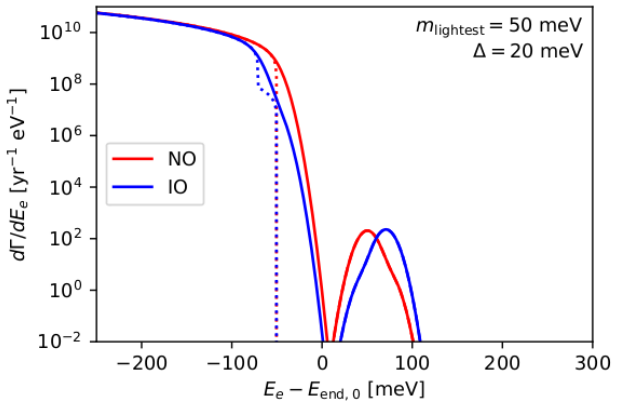
[Phys. Rev. 128, 1457]

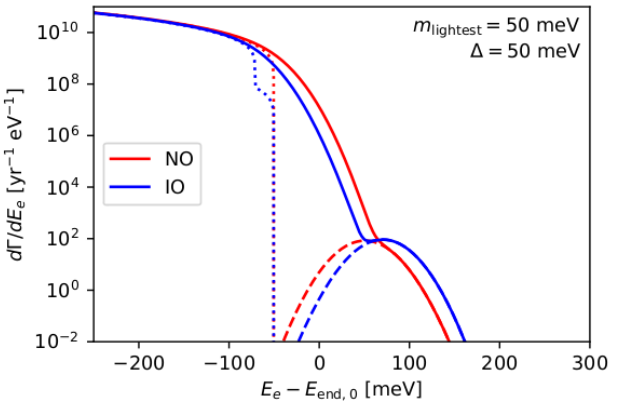
[AG.Cocco, G.Mangano, M.Messina JCAP 06(2007)015]

Realistic case







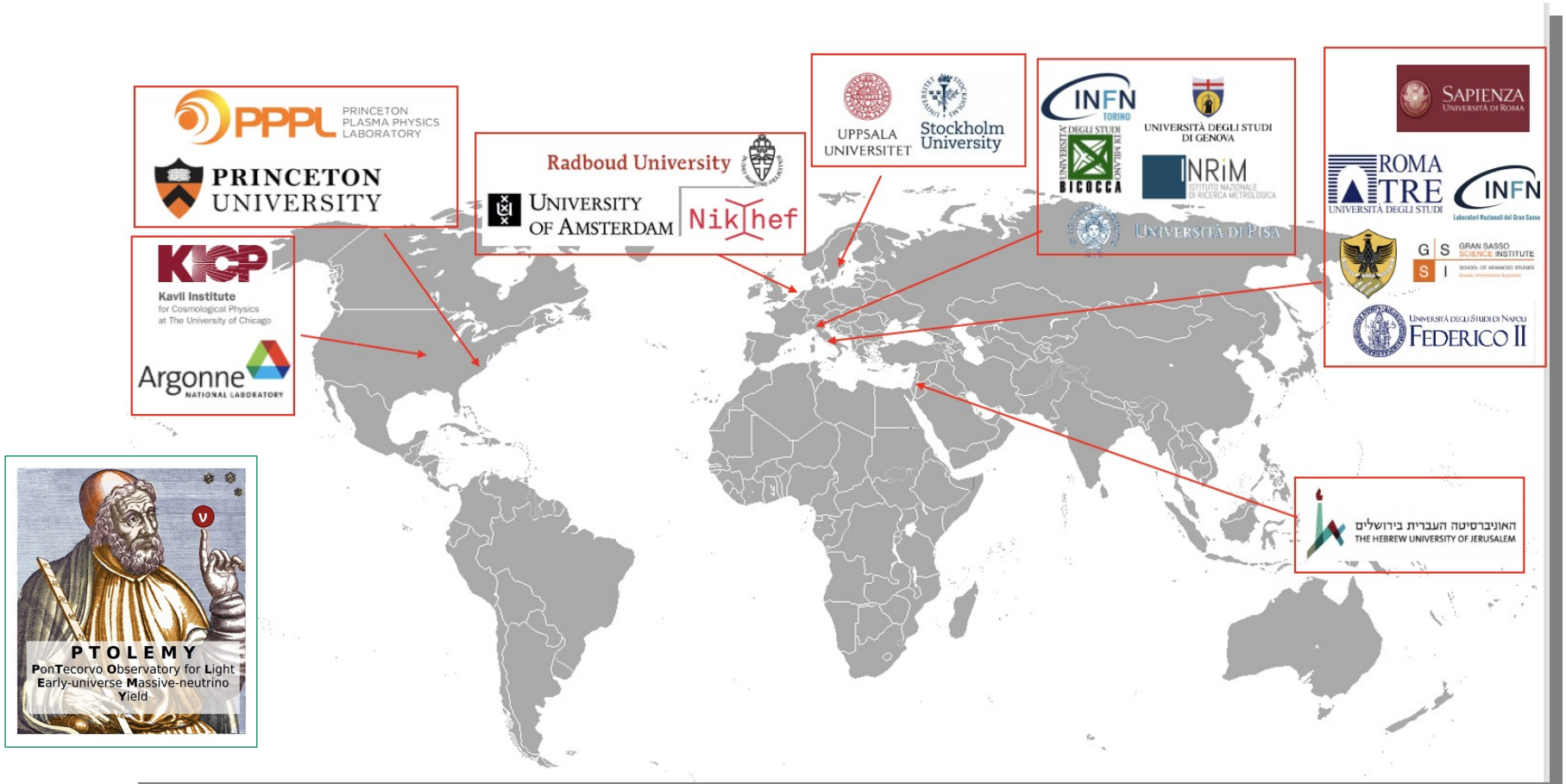


Depending of the **netruino mass scale**

Crucial for the **CNB** detection

Less stringent for neutrino **mass**

The PTOLEMY Collaboration



Coll. Meeting, Pollica, May 2024

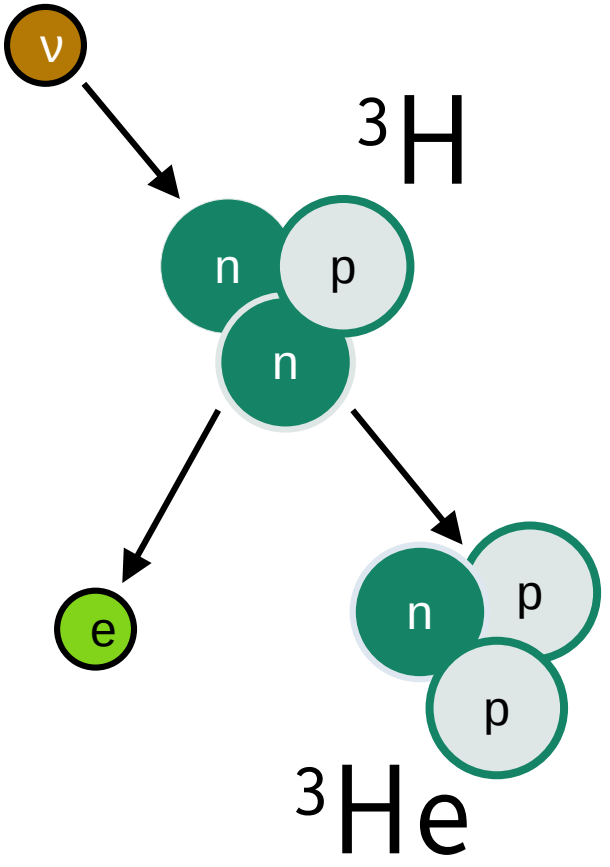
Tritium: the best candidate

★ **Low Q value:** $Q_0 = 18.6$ keV

★ **Reasonable halflife** $T_{1/2} = 12.3$ y
(high rate but not that fast)

★ **Simple nuclear structure,**
No nuclear structure corrections

★ Relatively **high cross section**
(constant $\sigma \sim 10^{-44}$ cm^2)



Requirements: solid state source

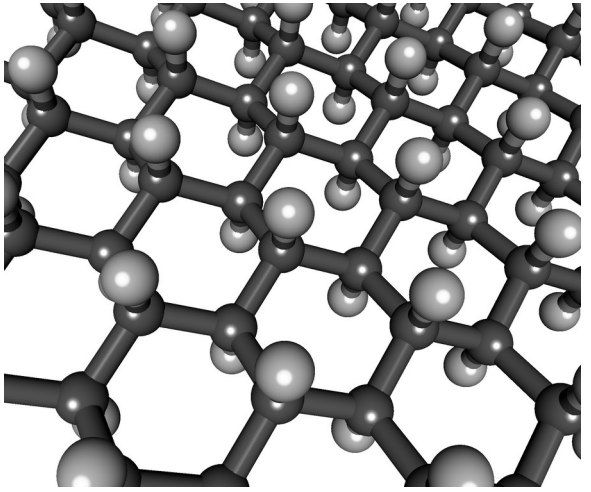
★ **Large target**, 100 g
8 event/y (Majorana), 4 event/y (Dirac)

★ **Low** target induced **smearing**

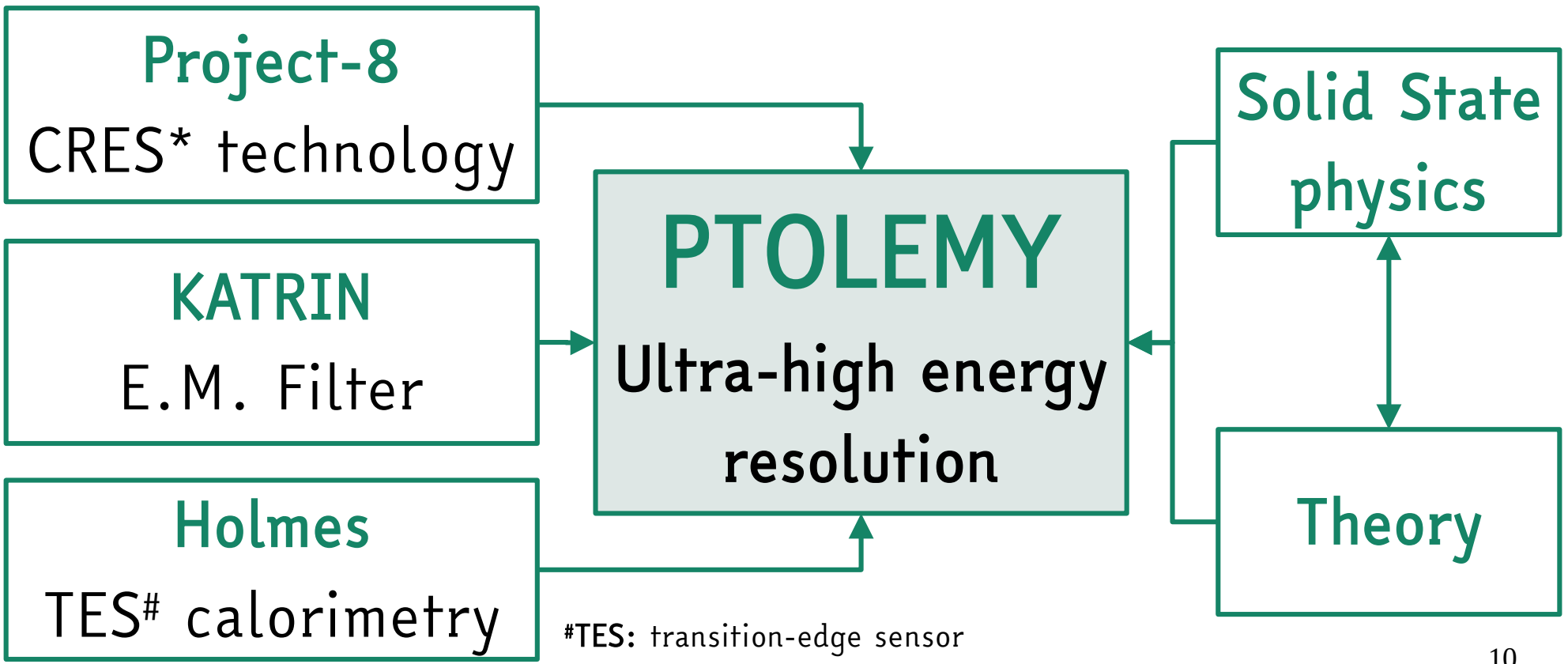
★ **High rate** (~ 10^{14} Bq/g) handling

★ **Small filter dimension** (~ 1m size)

★ **Ultra-high resolution** electron detection (~ 50 meV)



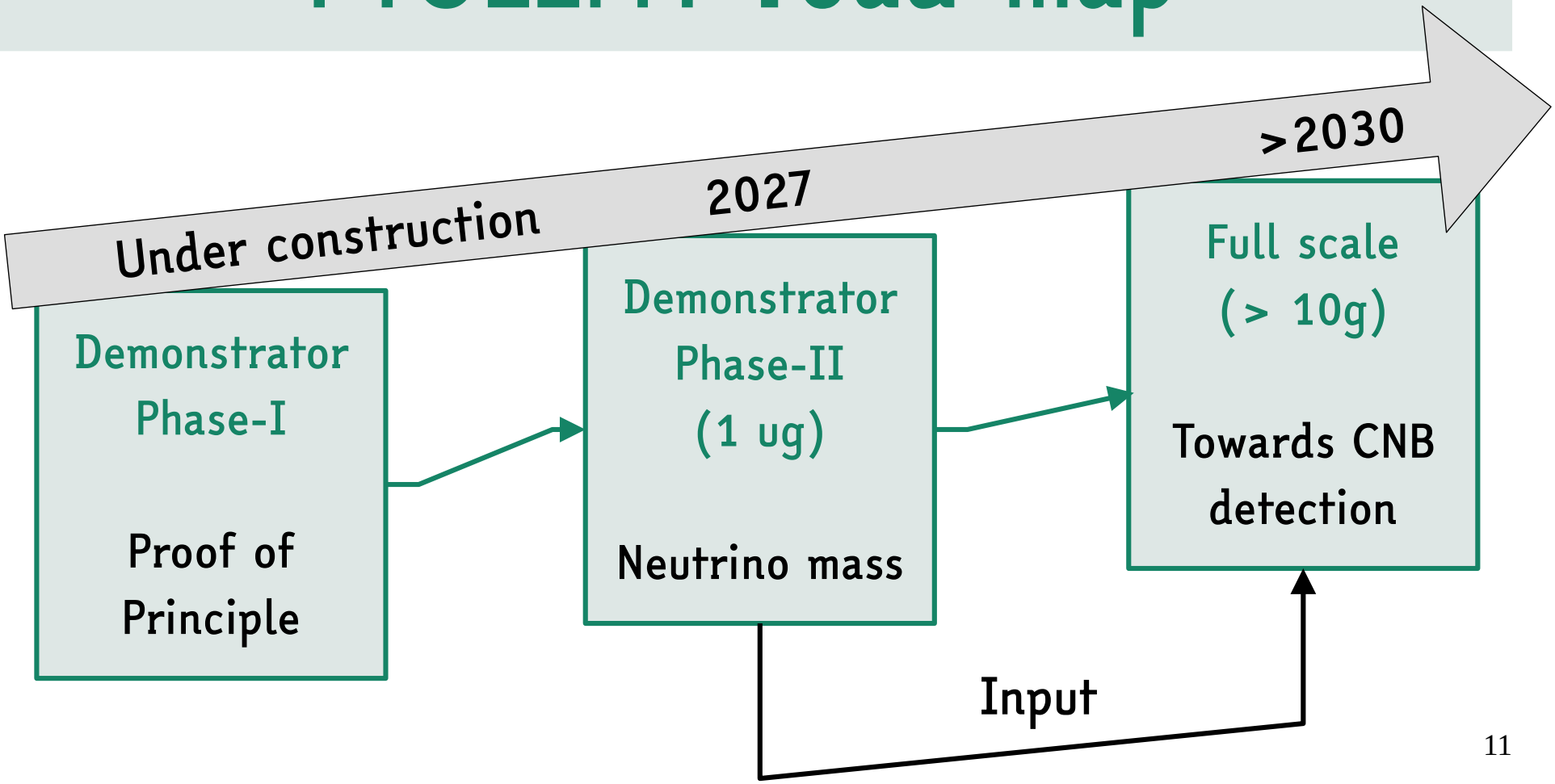
Technology combination



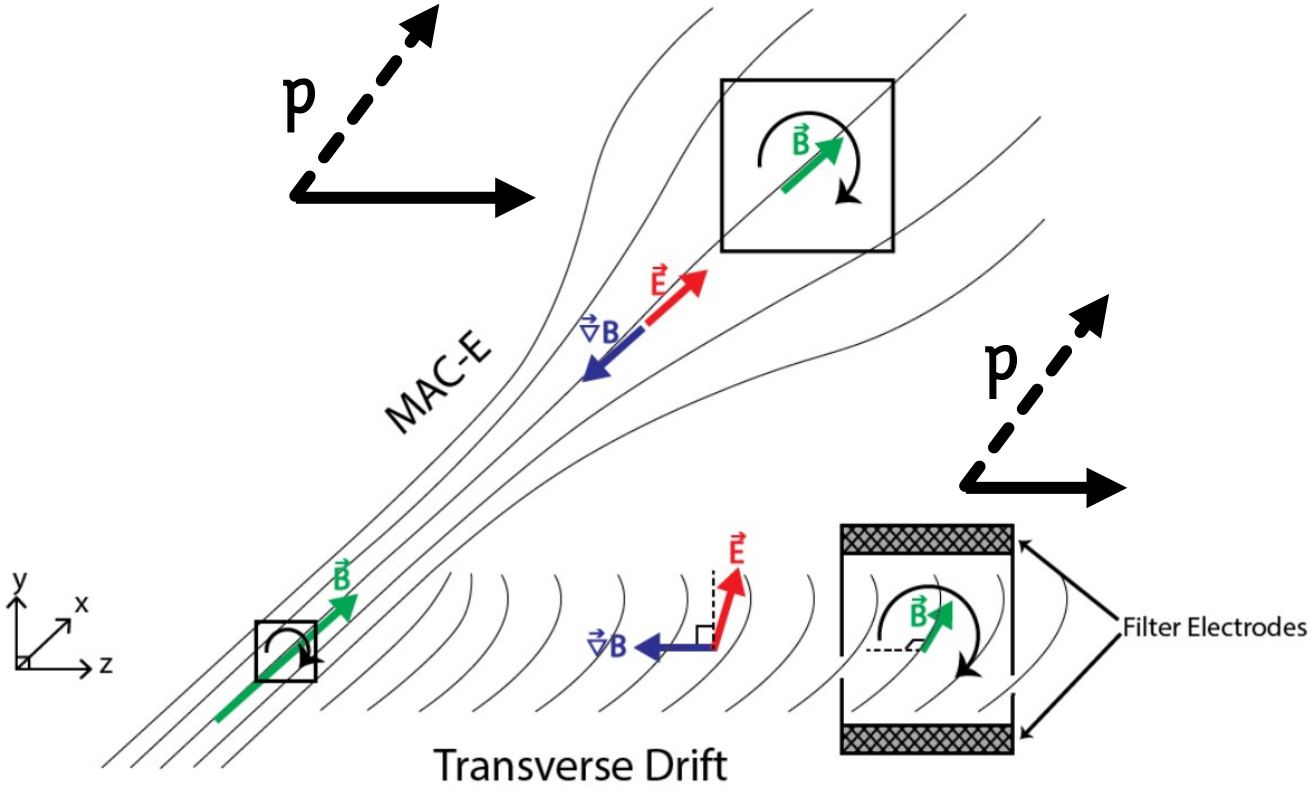
#TES: transition-edge sensor

*CRES: cyclotron radiationemission spectroscopy

PTOLEMY road-map



Transverse Drift Concept



MAC-E filter

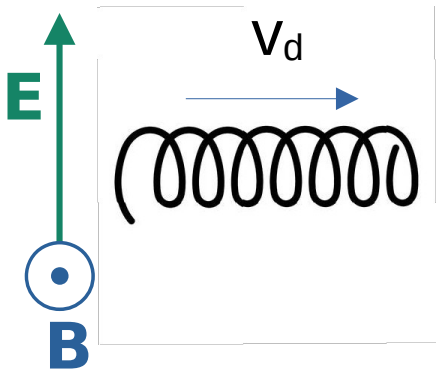
$$\vec{B} \parallel \nabla B \parallel \vec{E}$$

Transverse Drift

$$\vec{B} \perp \nabla B \perp \vec{E}$$

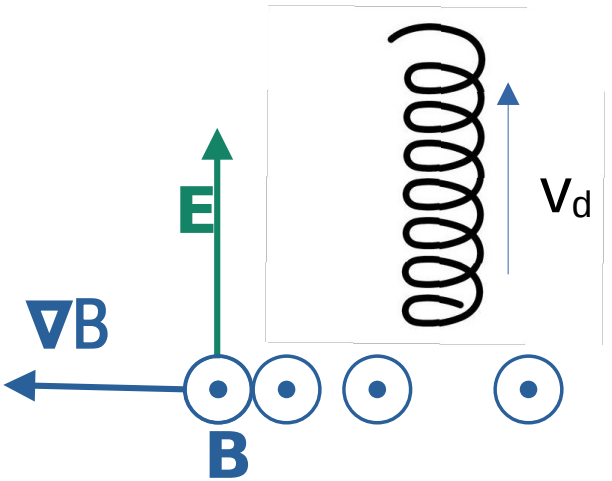
Guiding center

E x B drift



$$V_d = \frac{E}{B}$$

B x ∇B drift



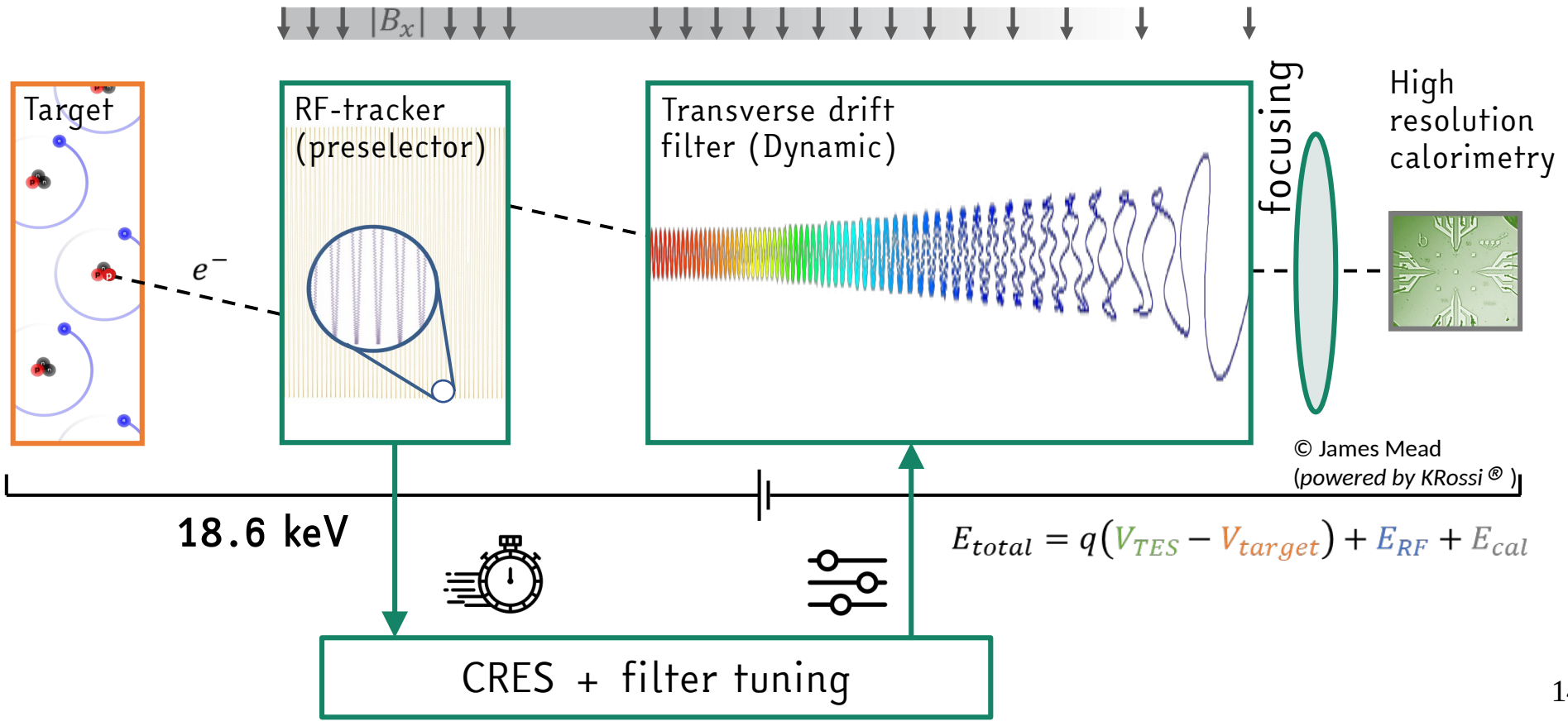
$$V_d = \mu \frac{|\vec{\nabla} B|}{B}$$

$$\mu = \frac{m_e v_\perp}{2B}$$

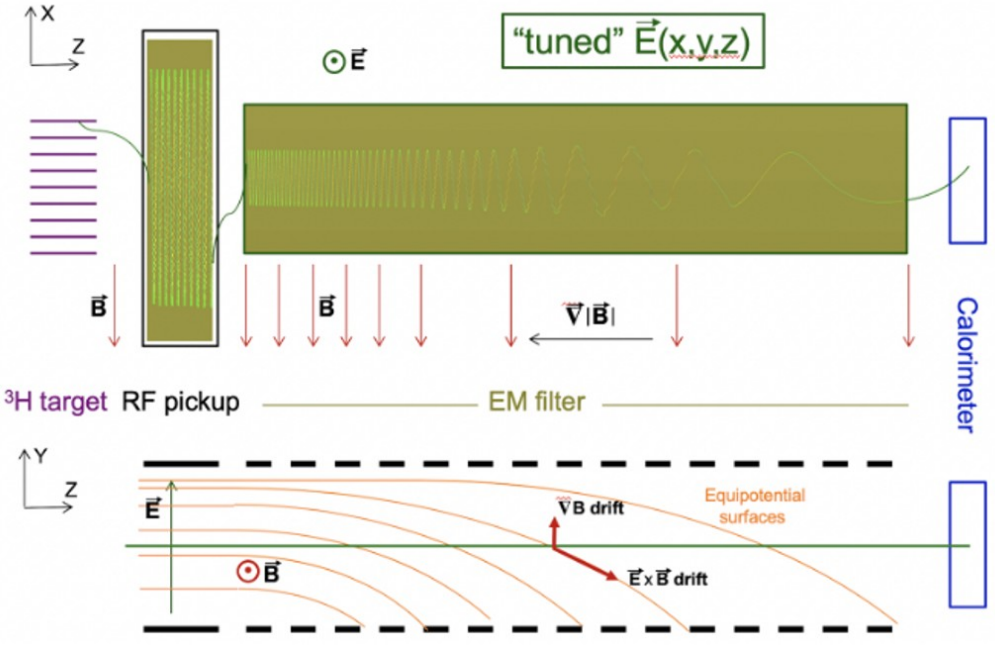
$$\vec{V}_d = (e\vec{E} - \mu\vec{\nabla}B) \times \frac{\vec{B}}{eB^2}$$

$$\frac{dK_\perp}{dt} = e\vec{E} \cdot \vec{V}_d$$

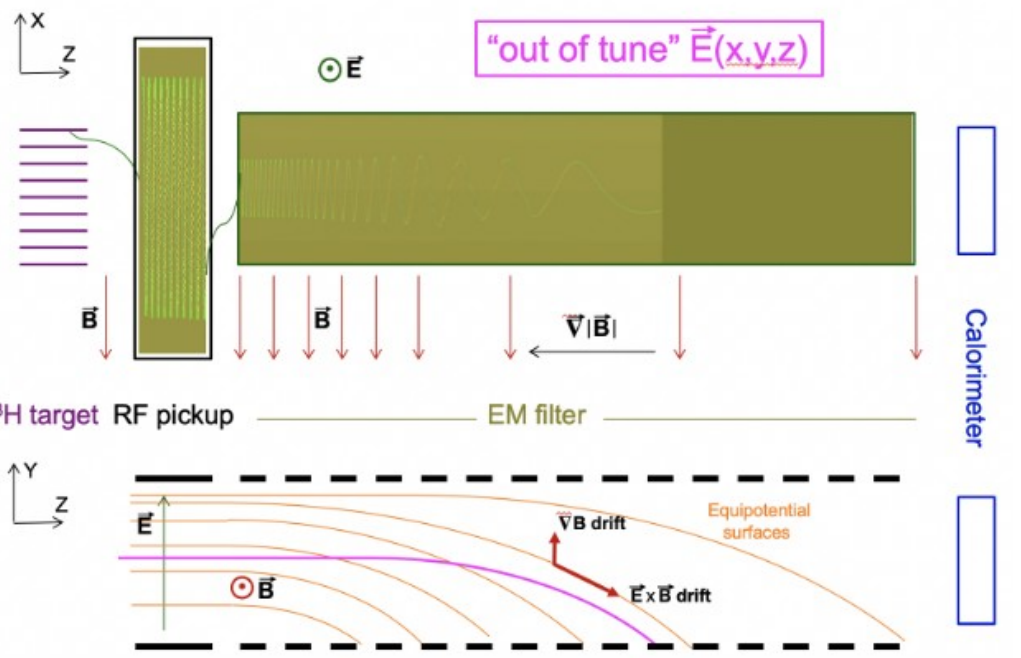
PTOLEMY detection concept



Filter tuning

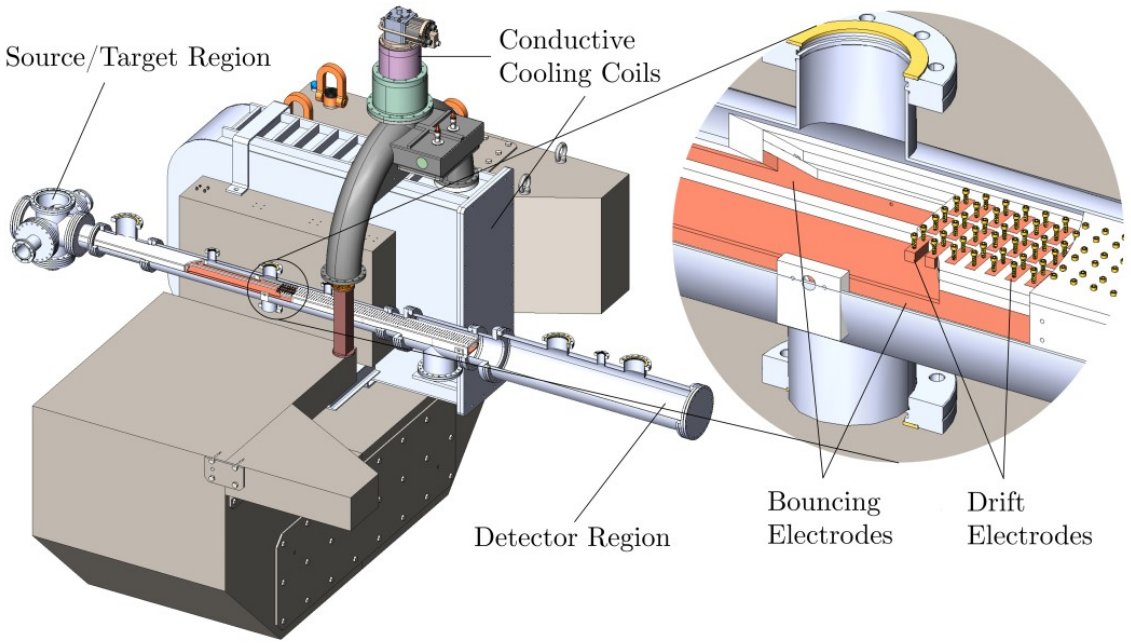


It passes



It doesn't pass

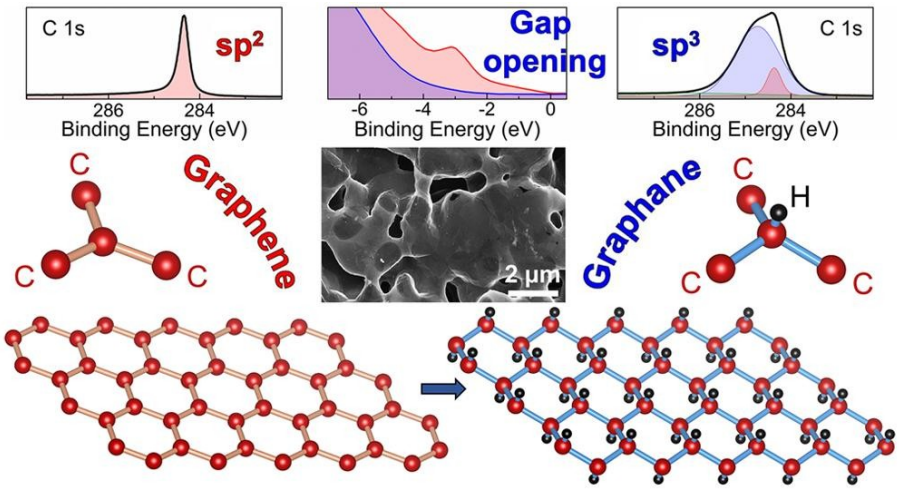
Demonstrator look



R&D of the parts (ongoing at LNGS)

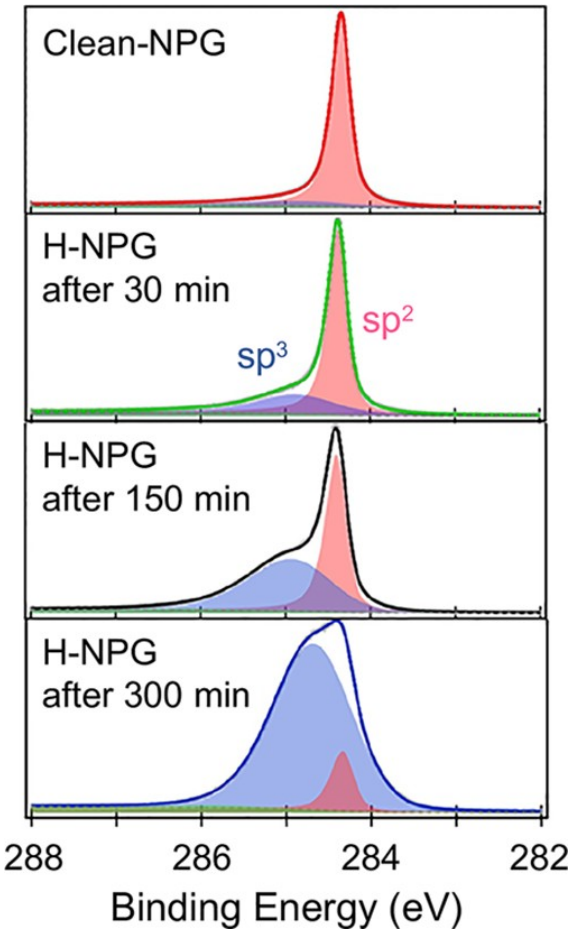
Final assembly (upon the arrival of the magnet, end of 2025)

Towards tritiated graphene

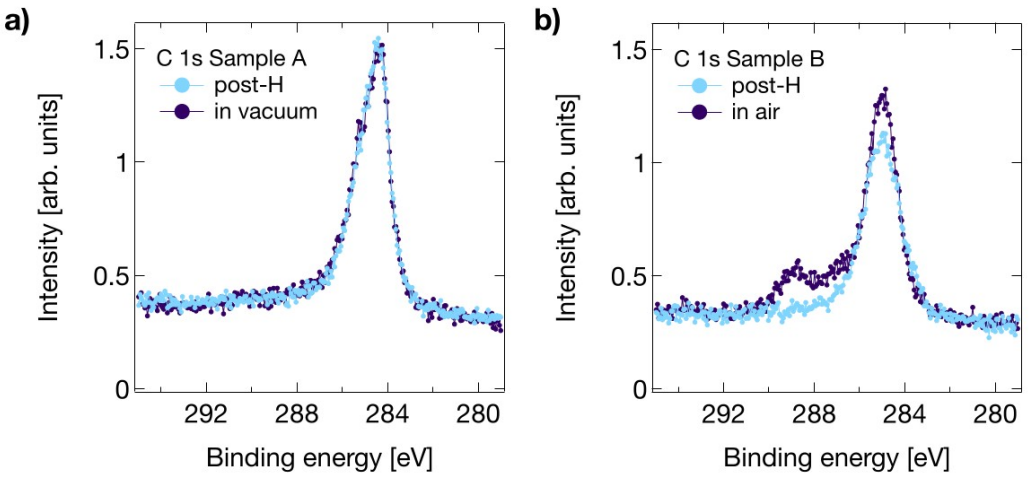


90% loading (record) on nano-porous graphene **[@La Sapienza]**

[Nano Lett. 2022, 22, 2971]



Towards tritiated graphene



- Stability in vacuum

[arXiv:2504.11853]

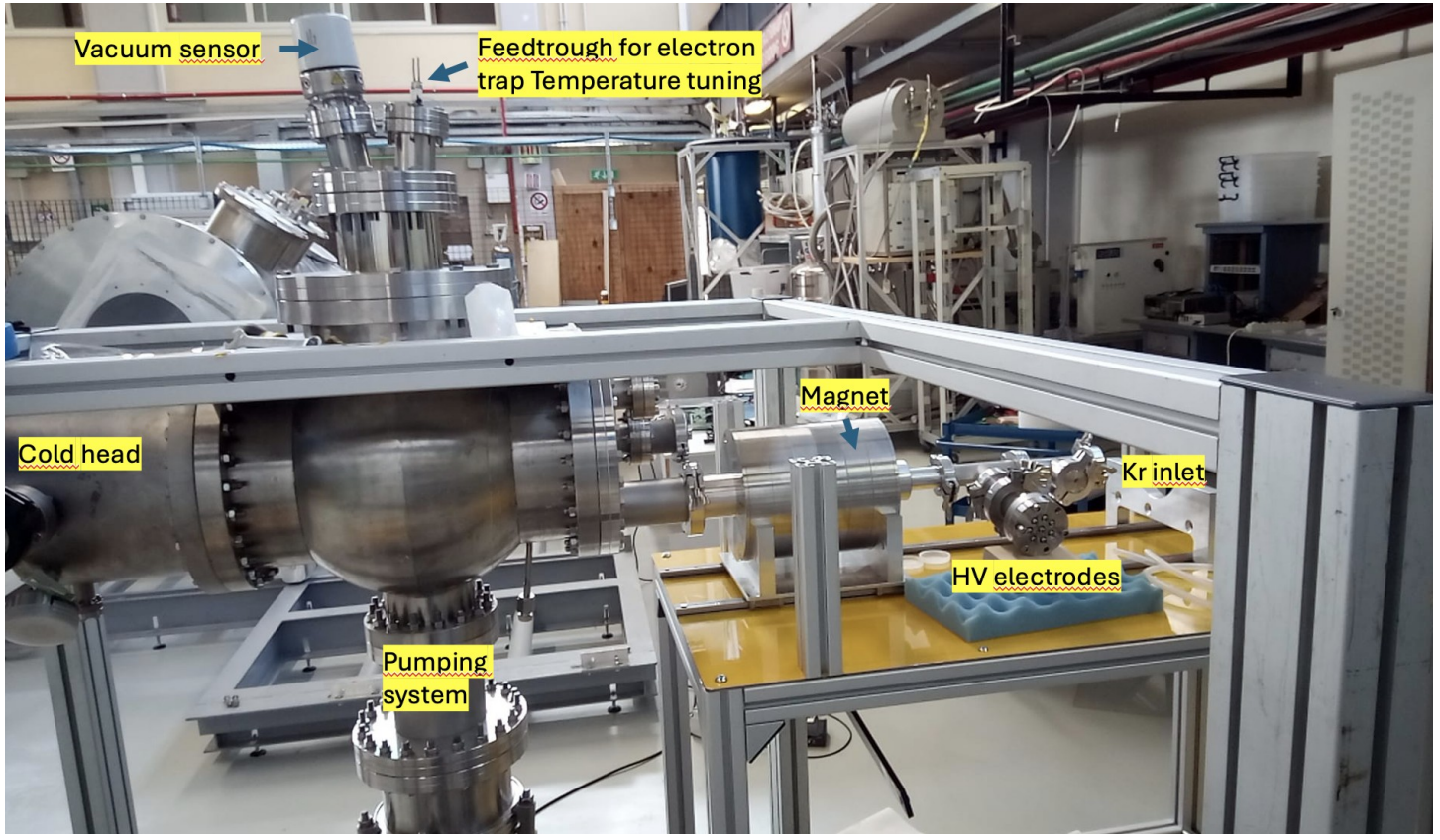
- electron transparency (ongoing)

[@Roma Tre]

Tritiated graphene handling

[^{3}H] In contact with UKAEA's Active Gas Handling Syste (tritium for JET, EU Tokamak)

CRES spectroscopy at LNGS

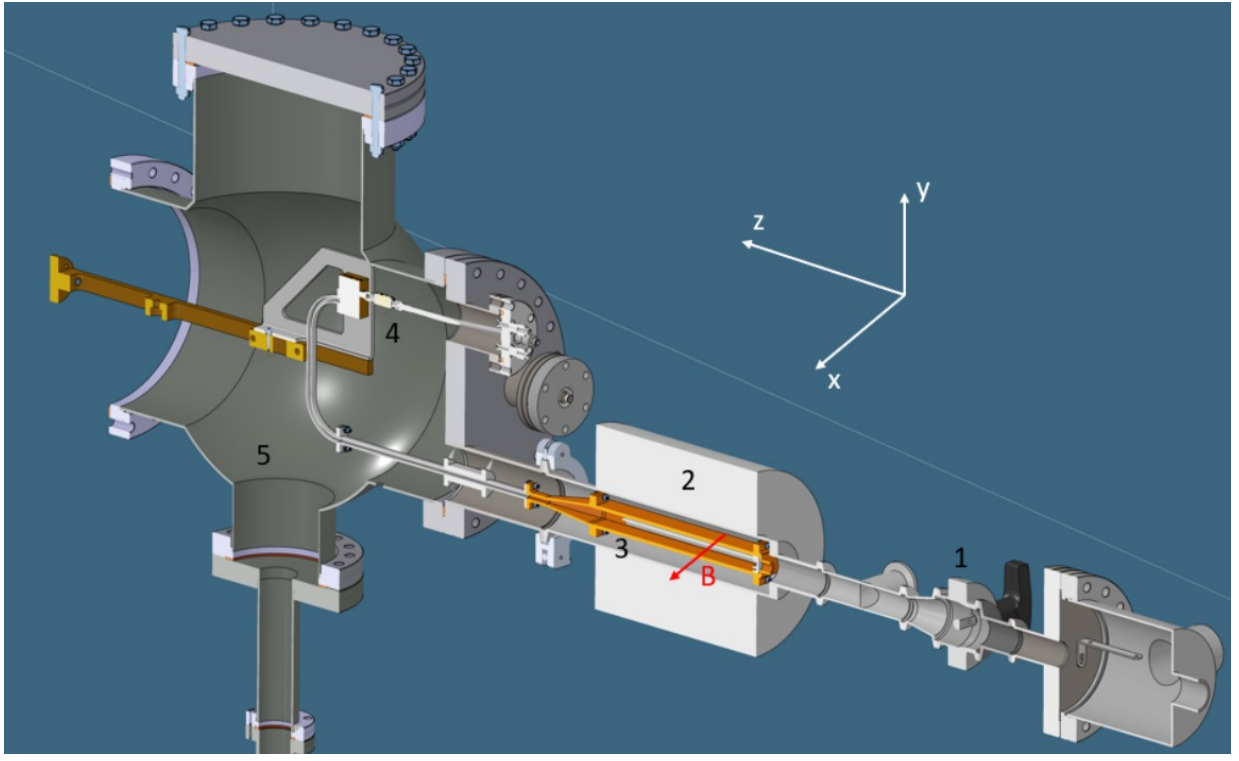


Experimental setup for RF detection

<10 eV resolution (10-100 μs)

^{83m}Kr calibration (32 keV)

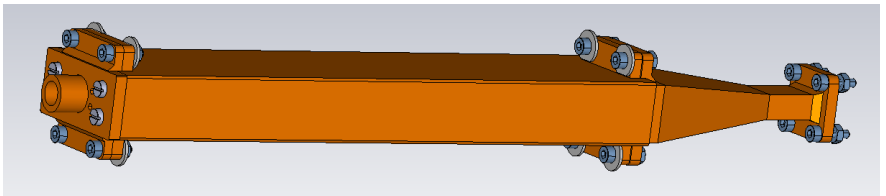
CRES spectroscopy at LNGS



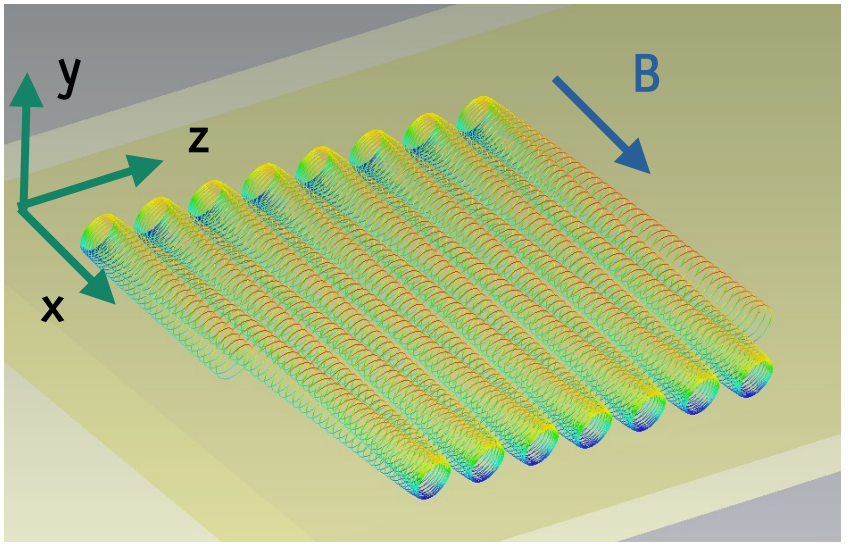
Feasibility study per the filter pre-selector

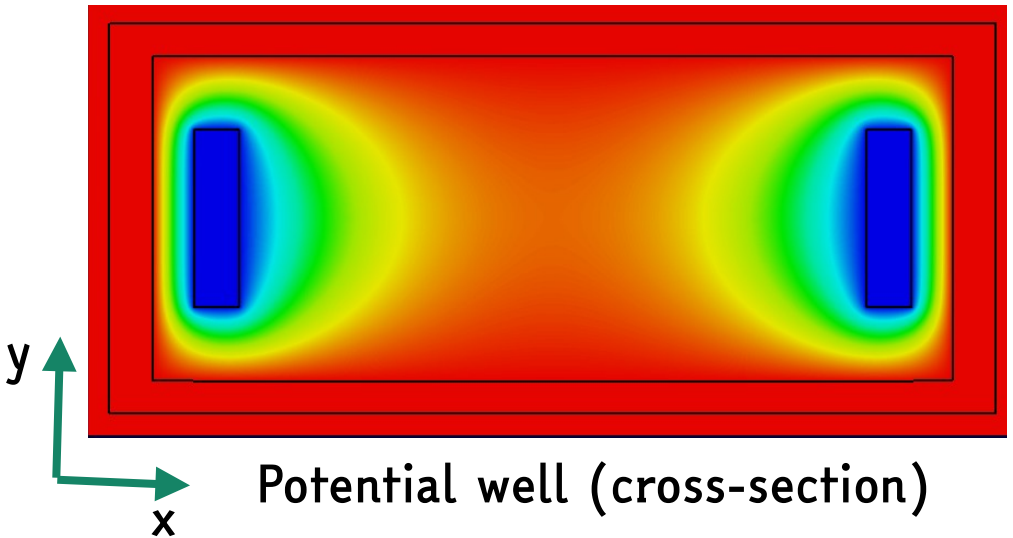
Reconstruction of total momentum and transverse component

Detection principle

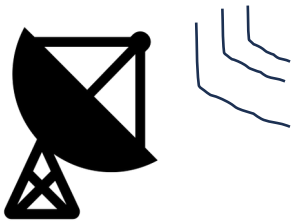


Wave guide



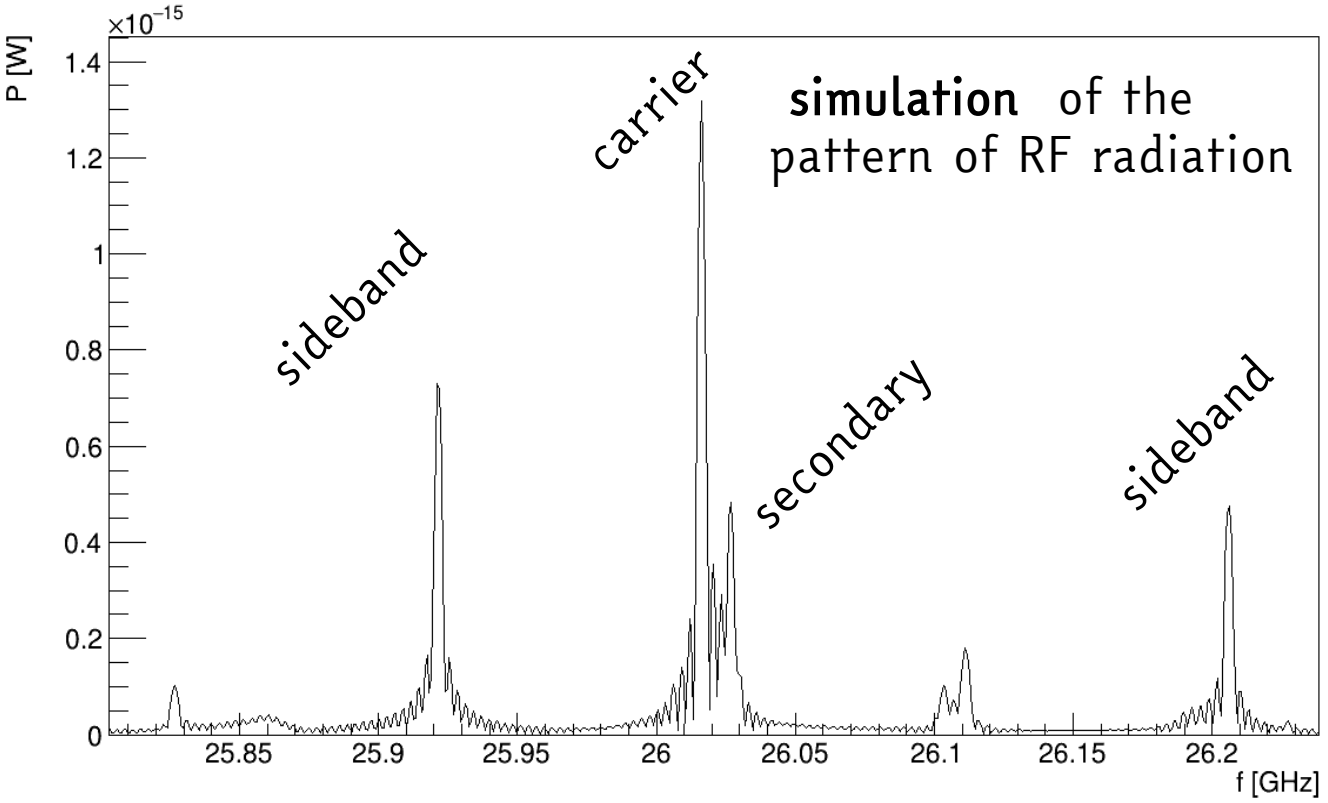


Potential well (cross-section)



Bouncing motion in the trap (simulation)

Kinematic reconstruction



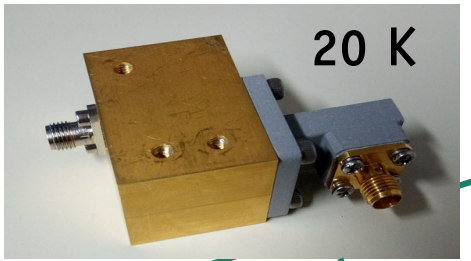
The **carrier** gives the total kinetic energy (**K**)

$$f_c = \frac{1}{2\pi}\frac{eB}{m}\frac{1}{K/m+1}$$

Δf with the **sidebands** is related to $K_{//}$

Detection chain

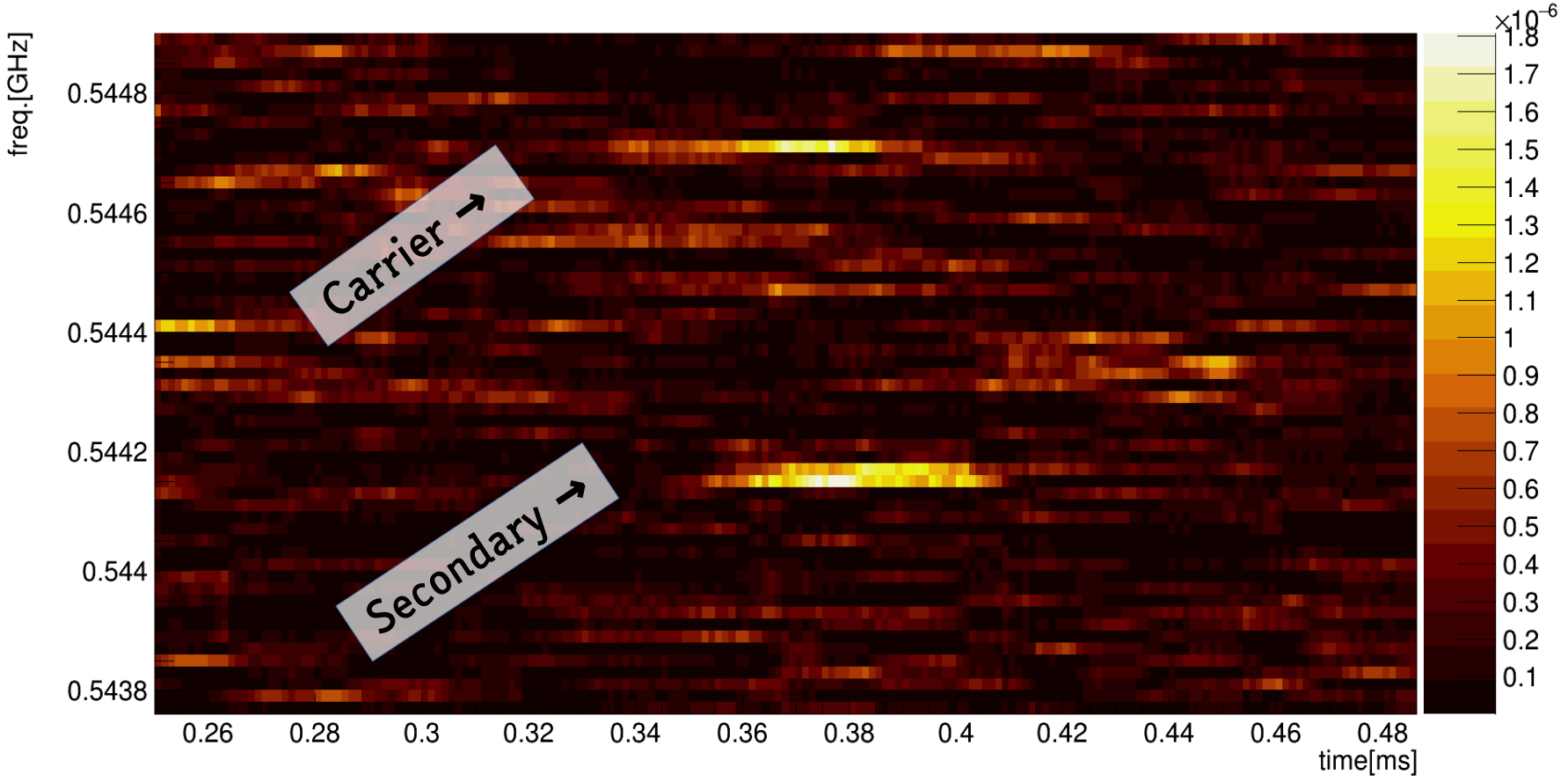
INPUT
f = 26 GHz
P = 1fW



[@Nikhef]

OUTPUT
f = 550 MHz
P = 2μW

Example of candidate

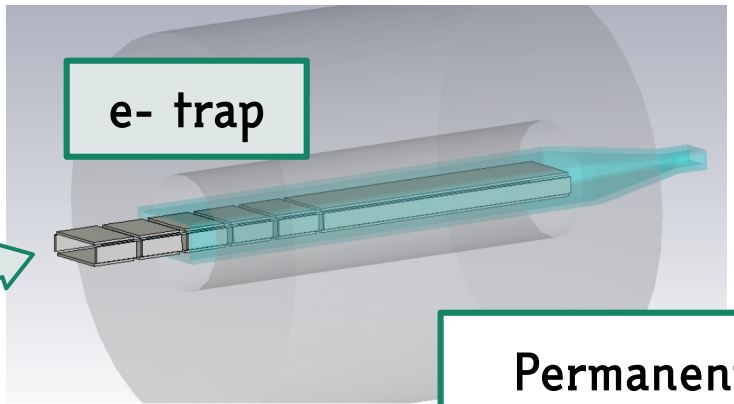


e-gun calibration

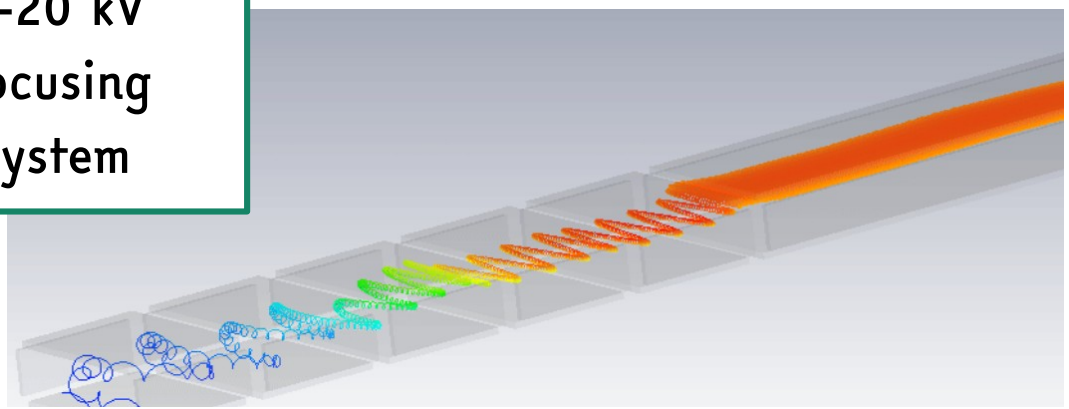
KIMBALL PHYSICS
Excellence in Electron and Ion Optics

EMG-4212 / EGPS-3212
ELECTRON SOURCE / POWER SUPPLY

Electron gun
0-20 kV
Focusing
system

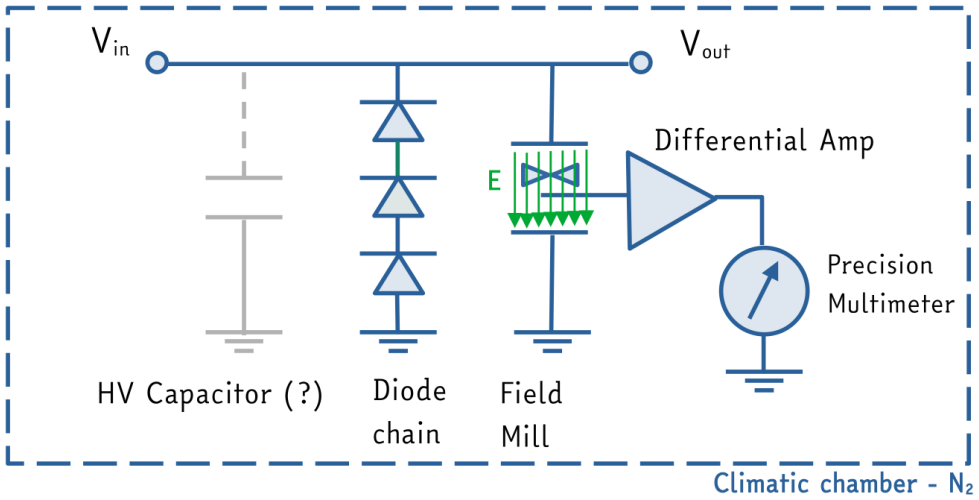


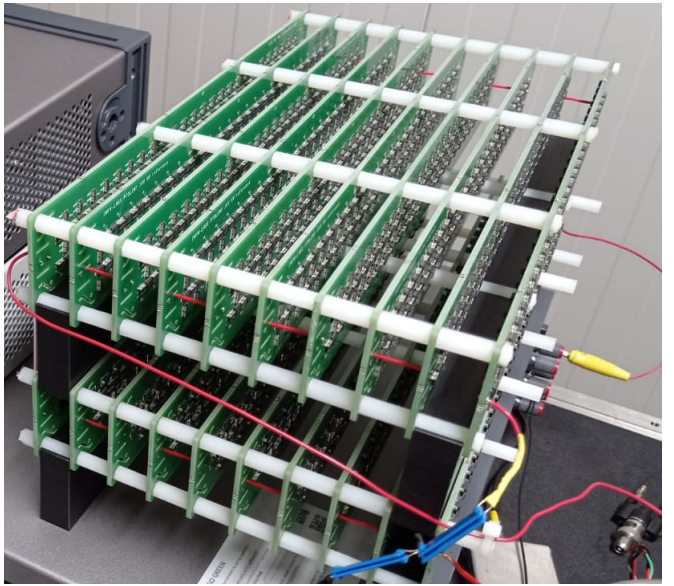
Permanent
Magnet

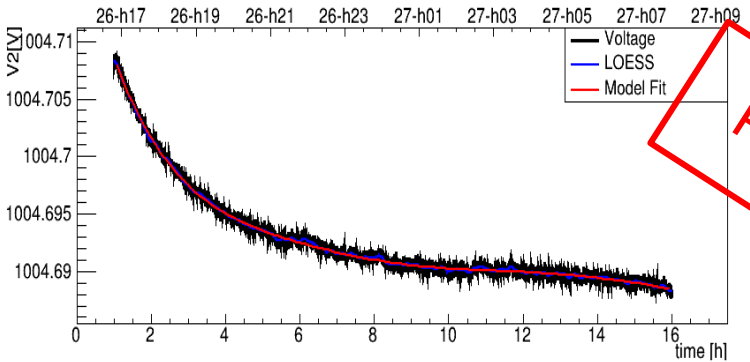


Study and test of the calibrated electron injection into the CRES trap

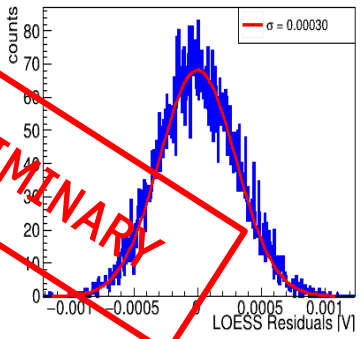
HV High precision stability (LNGS)

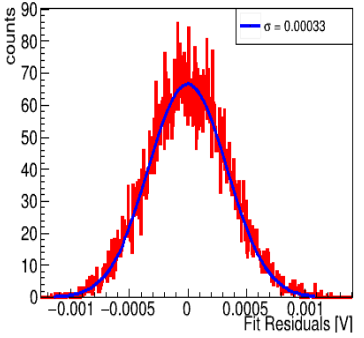






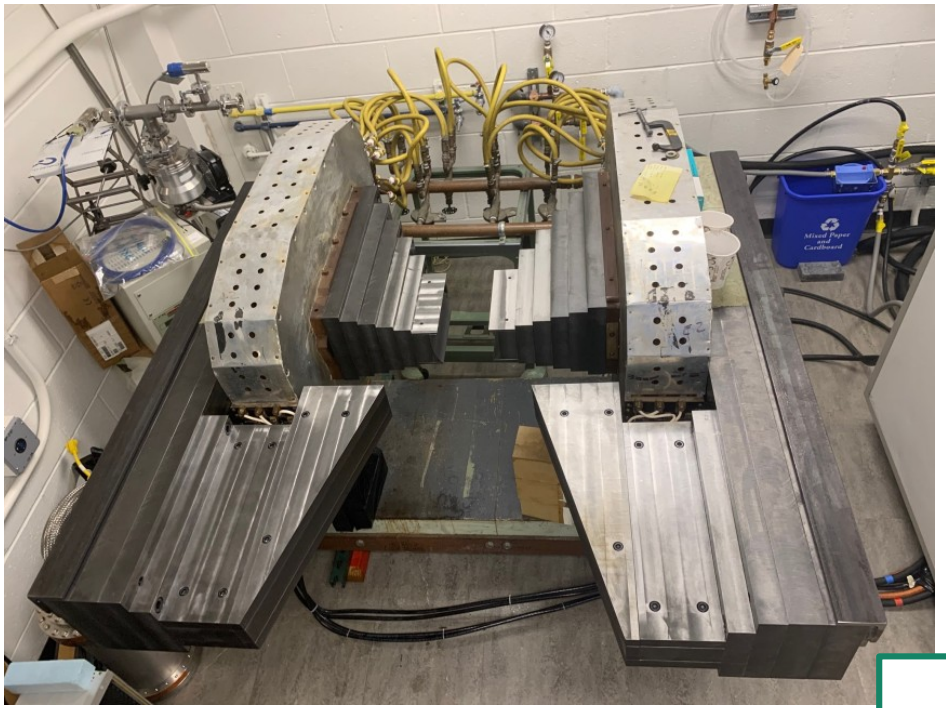
PRELIMINARY



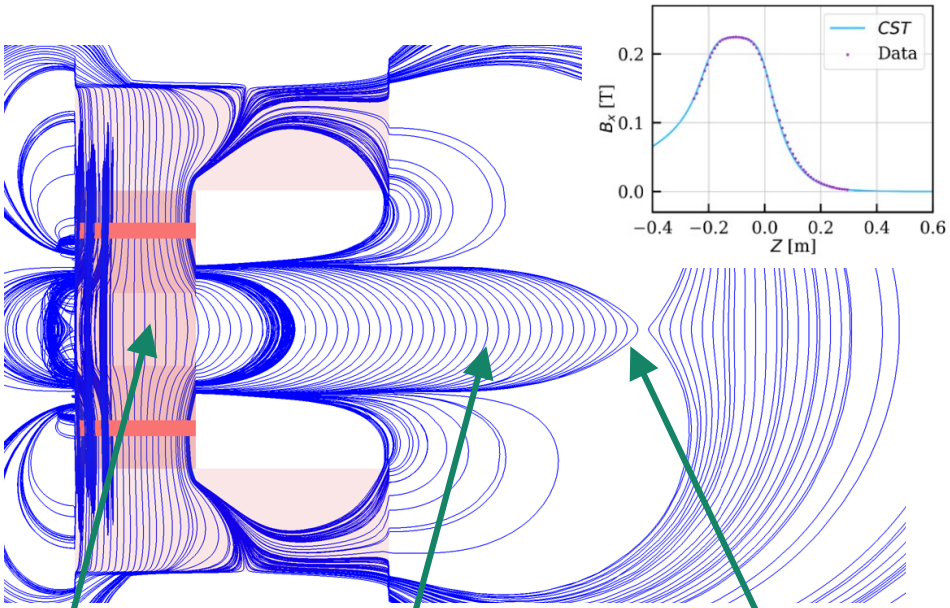


Single board (1 kV)
σ = 0.3 mV [0.3 ppm]

Prototype magnet



@PRINCETON

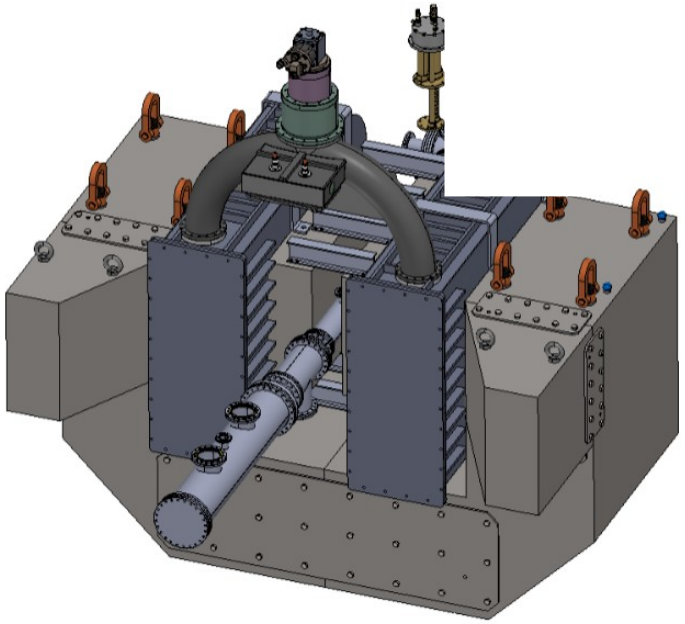


B = const

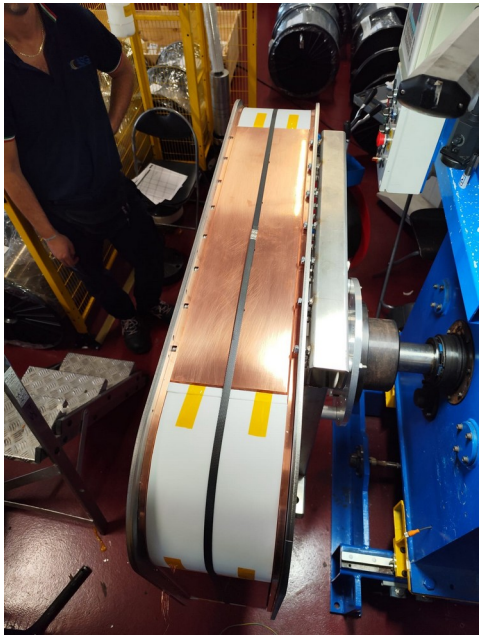
B ~ ezp(-z)

Saddle point

Superconductive magnet

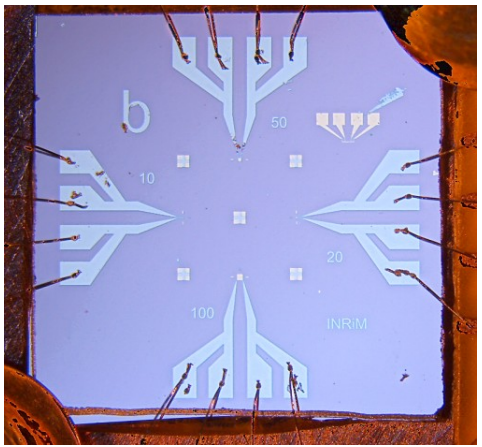


★ Uniform region:
~10 x 10 x 80 cm
★ ΔB/B (1T) ~ 10^{-4}

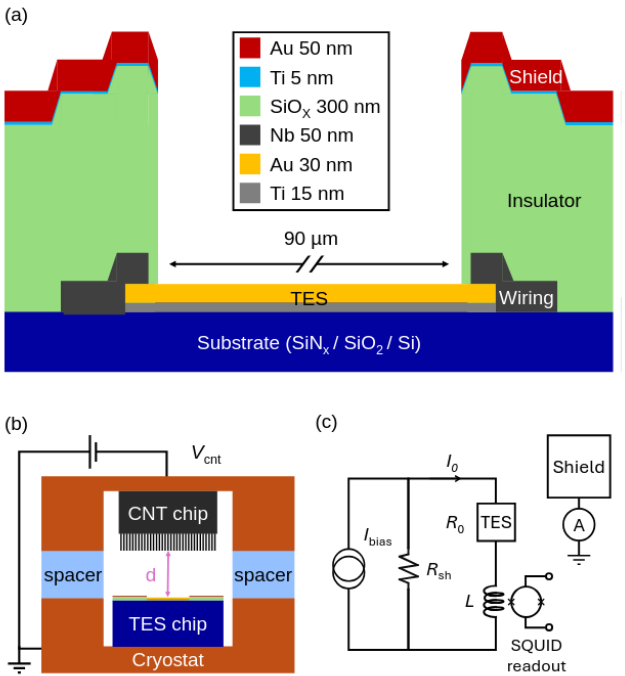


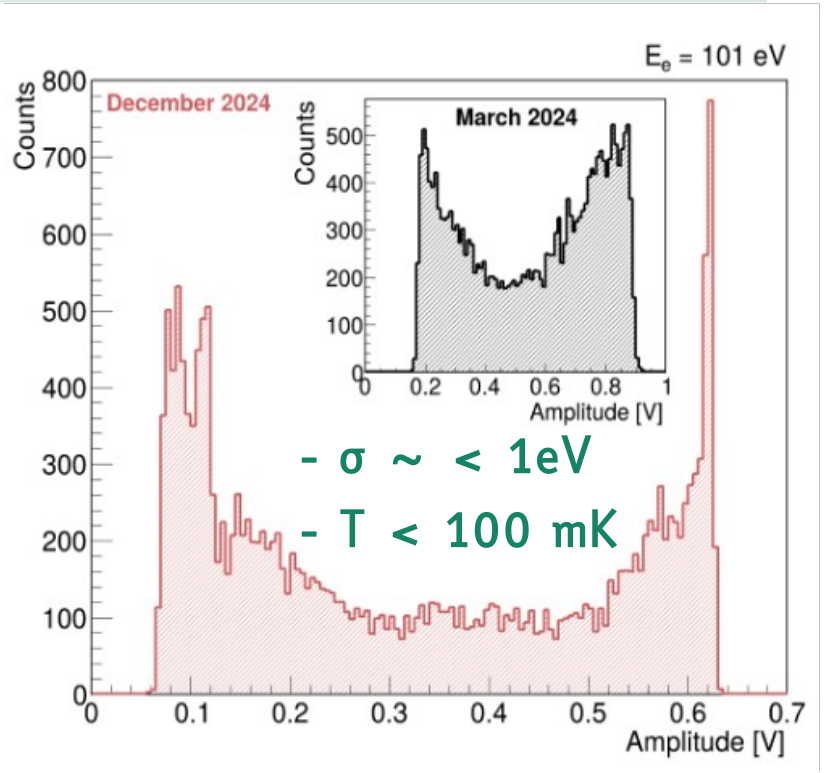
@ASG/Suprasys,
Genova, Italy/Spain

Electron detection with TES



[@INRIM]

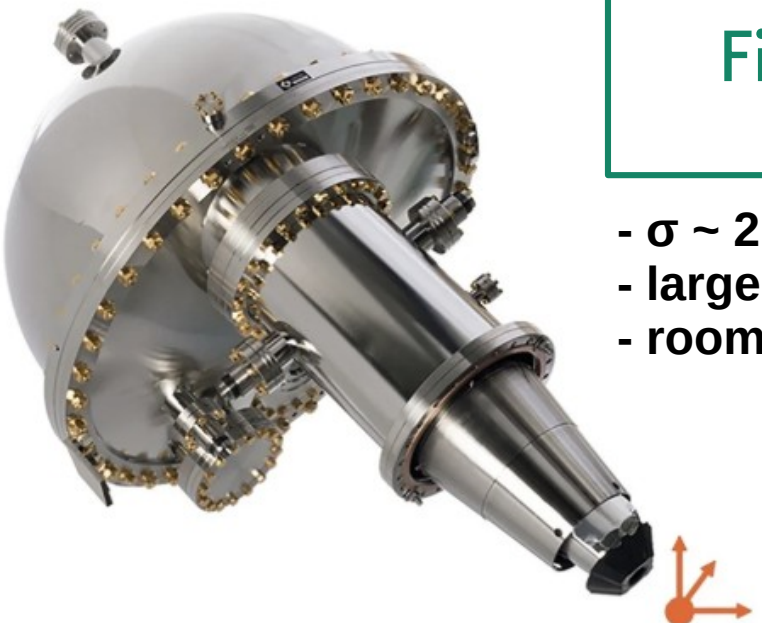




[Phys.Rev.Applied 22 (2024) 4, L041007]

Hemispherical Energy Analyzer

scientaomicron

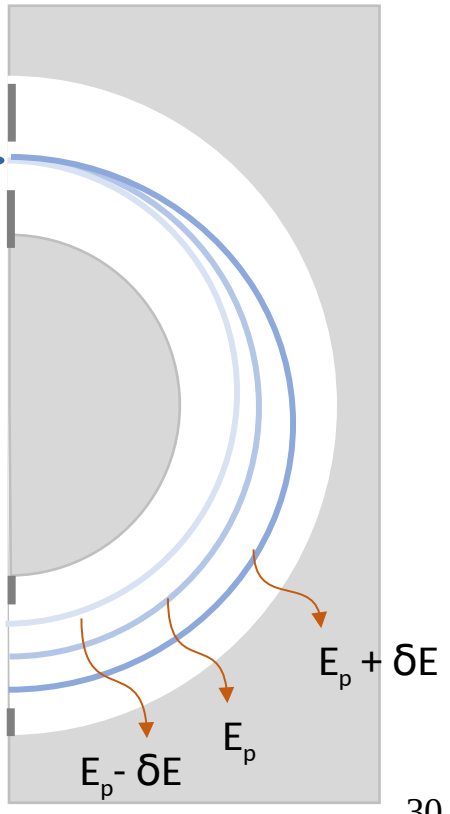


Ptolemy Filter

- σ ~ 2meV
- large acceptance
- room T

Einzel lens

MCP detector
x-y reconstruction
with delay line



Filter modeling

- Given the following field configuration:

$$V(x,y,z) = T'_{\perp} \sin\left(\frac{y}{\lambda}\right) e^{-z/\lambda}$$

$$E_x = 0$$
$$E_y = \frac{T'_{\perp}}{\lambda} \cos\left(\frac{y}{\lambda}\right) e^{-z/\lambda}$$
$$E_z = -\frac{T'_{\perp}}{\lambda} \sin\left(\frac{y}{\lambda}\right) e^{-z/\lambda}$$

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

- The drift balancing condition along z is:

$$\boldsymbol{V}^{y}_{E\times B}(z) = \boldsymbol{V}_{\nabla B}(z)$$

$$\frac{\boldsymbol{E}\times\boldsymbol{B}}{B_x^2} = -\frac{\boldsymbol{\mu}\times\boldsymbol{\nabla}_{\perp}\boldsymbol{B}(\boldsymbol{z})}{qB(z)}$$

- With $\boldsymbol{x} \ll \boldsymbol{\lambda}$,

$$\frac{E_z}{B_x}\hat{\boldsymbol{y}} = -\frac{\mu}{qB_x}\frac{dB_x}{dz}\hat{\boldsymbol{y}}$$
$$\approx \frac{E_z}{B} = -\frac{\mu}{qB}\frac{\partial B_x}{\partial z}$$
$$-\frac{T'_{\perp}}{B_0\lambda}\sin\left(\frac{y_0}{\lambda}\right) = \frac{\mu}{q\lambda}$$

- Solving for $T'_{\perp}$ and rewriting $\mu = \frac{T_{\perp 0}}{B_0 e^{-z_0/\lambda}}$,

$$T'_{\perp} = -\frac{T_{\perp 0} e^{z_0/\lambda}}{q\sin\left(\frac{y_0}{\lambda}\right)} = -\frac{T_{\perp 0} e^{z_0/\lambda}}{\sin\left(\frac{y_0}{\lambda}\right)}\ [\mathrm{eV}]$$

- Rearranging,

$$\boxed{T_{\perp 0} = -T'_{\perp}\sin\left(\frac{y_0}{\lambda}\right) e^{-z_0/\lambda}}$$

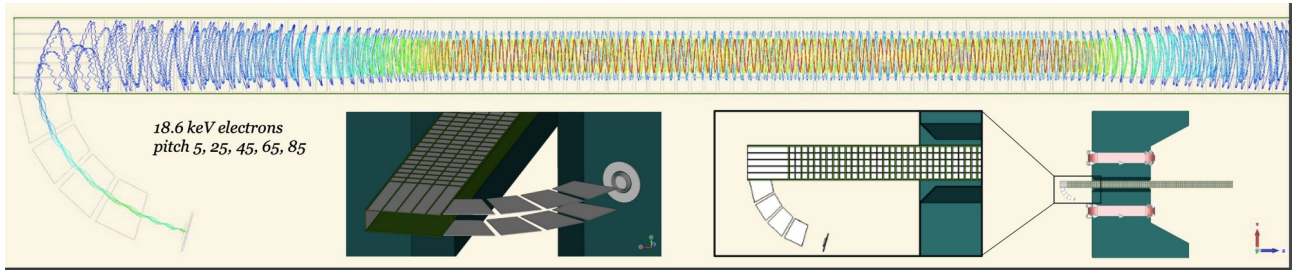
Analytical guess

[JINST 17 (2022) 05, P05021]

ExB arbitrarily slowed down in constant region

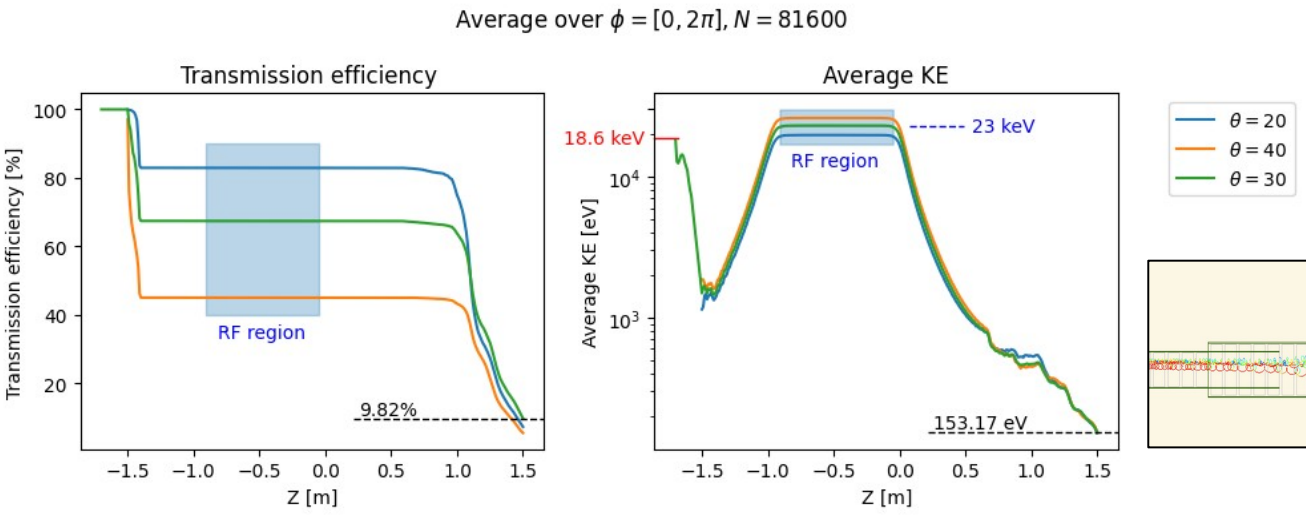
[arXiv:2503.10025]

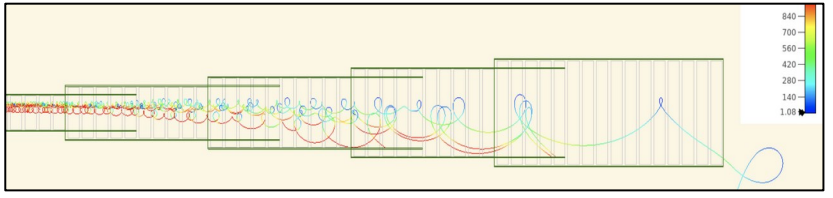
Simulations



TOOLS:

- COMSOL®
- CST®
- Kassiopeia®
- lorentz4

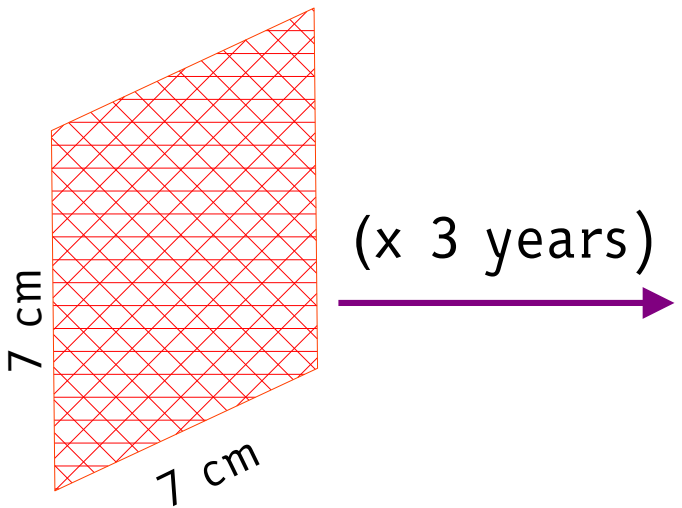




Sensitivity to neutrino mass

$$N_{dec} = \left(\frac{m_{\text{source}} \mathcal{N}_A}{A_{(^3H)}} (1 - e^{-t_{\text{expo}}/\tau_{^3H}}) \right) \times 0.5 \simeq 2.2 \cdot 10^{16} \text{events}$$

Efficiency
for total
Events: 50%
Exposure: 3 y



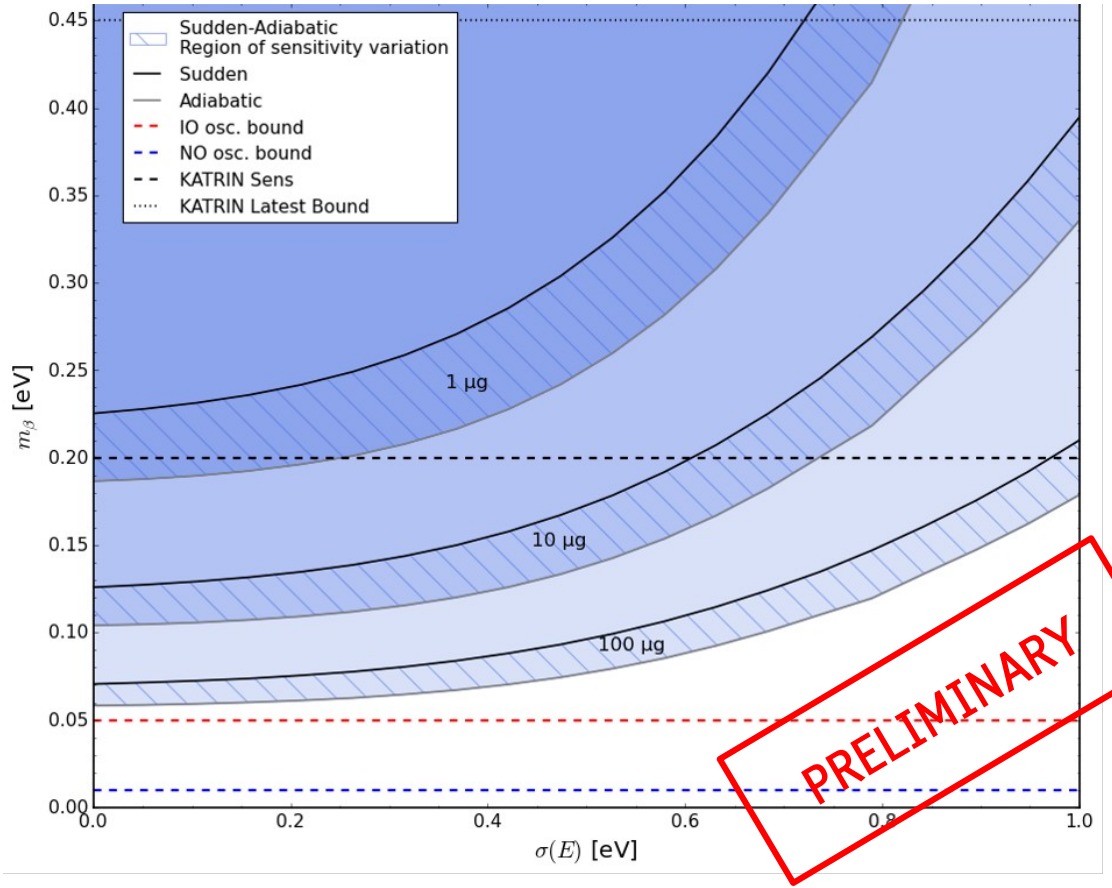
ρ = 0.2 mg/m²
(full loading)

→ 1 µg

716 MBq
(19.3 mCi)

Realistic sensitivity

From profile likelihood



★ Weakly dependent upon energy resolution (>400meV)

★ 1 μg: competitive with the forthcoming generation

★ 100 μg (0.5 m^2) close to probe the IO scenario

Conclusions

★ **Neutrinos** are a **unique portal** to physics beyond the Standard Model and cosmology.

★ The PTOLEMY project, in two steps, aims at measuring the **neutrino mass** and **paving the way for CNB detection**.

★ The **Demonstrator** is being built at LNGS—a huge effort bringing together different technologies and expertise to **break through to ultra-high-precision energy resolution in beta spectroscopy.**

Collaborators are really welcome!

Thank you very much for your attention!

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God bless Ptolemy!