The PTOLEMY project results and status

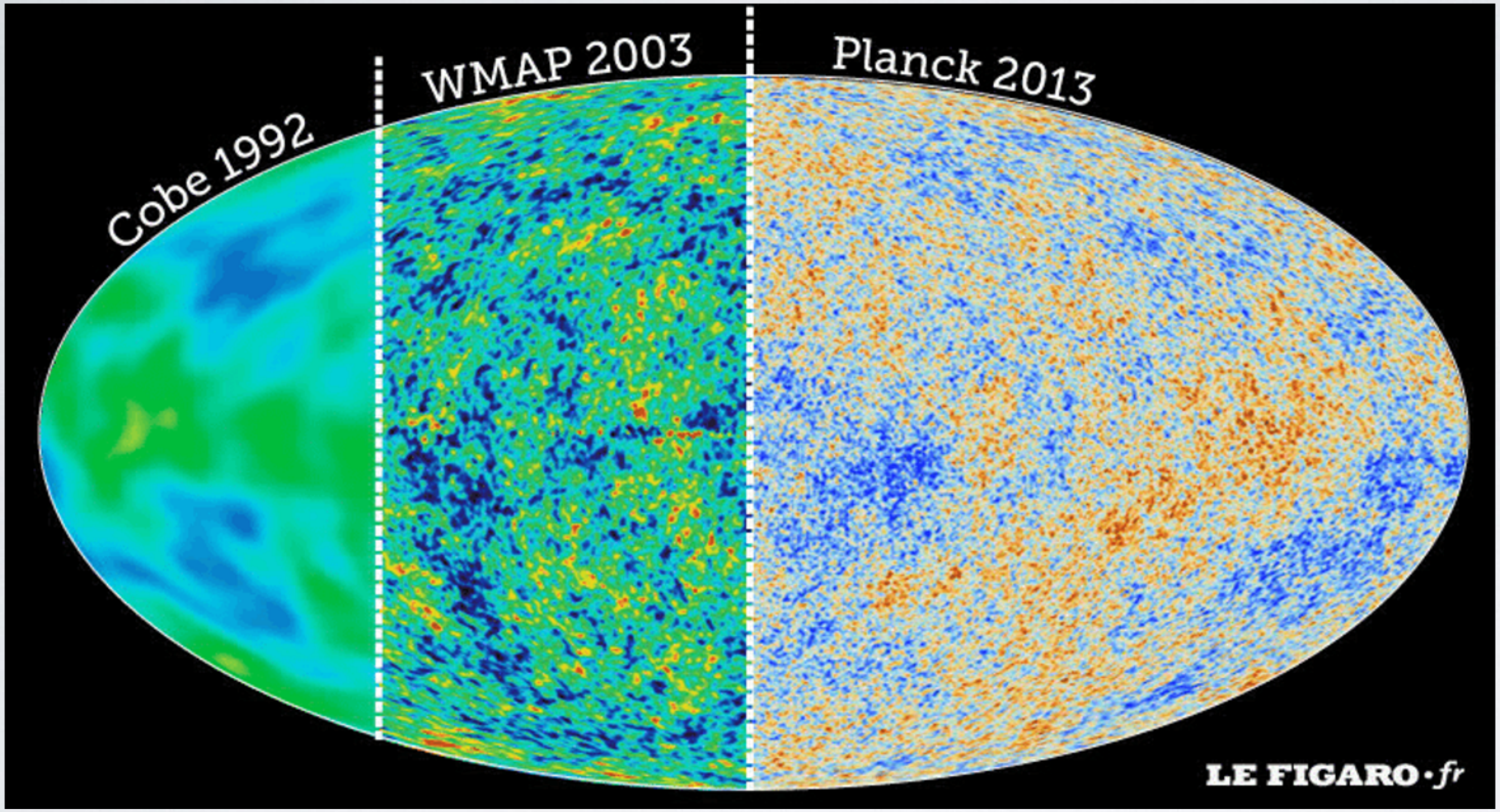
M Messina, INFN-LNGS researcher

OUTLINE

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

The Gold-mine of Cosmologist

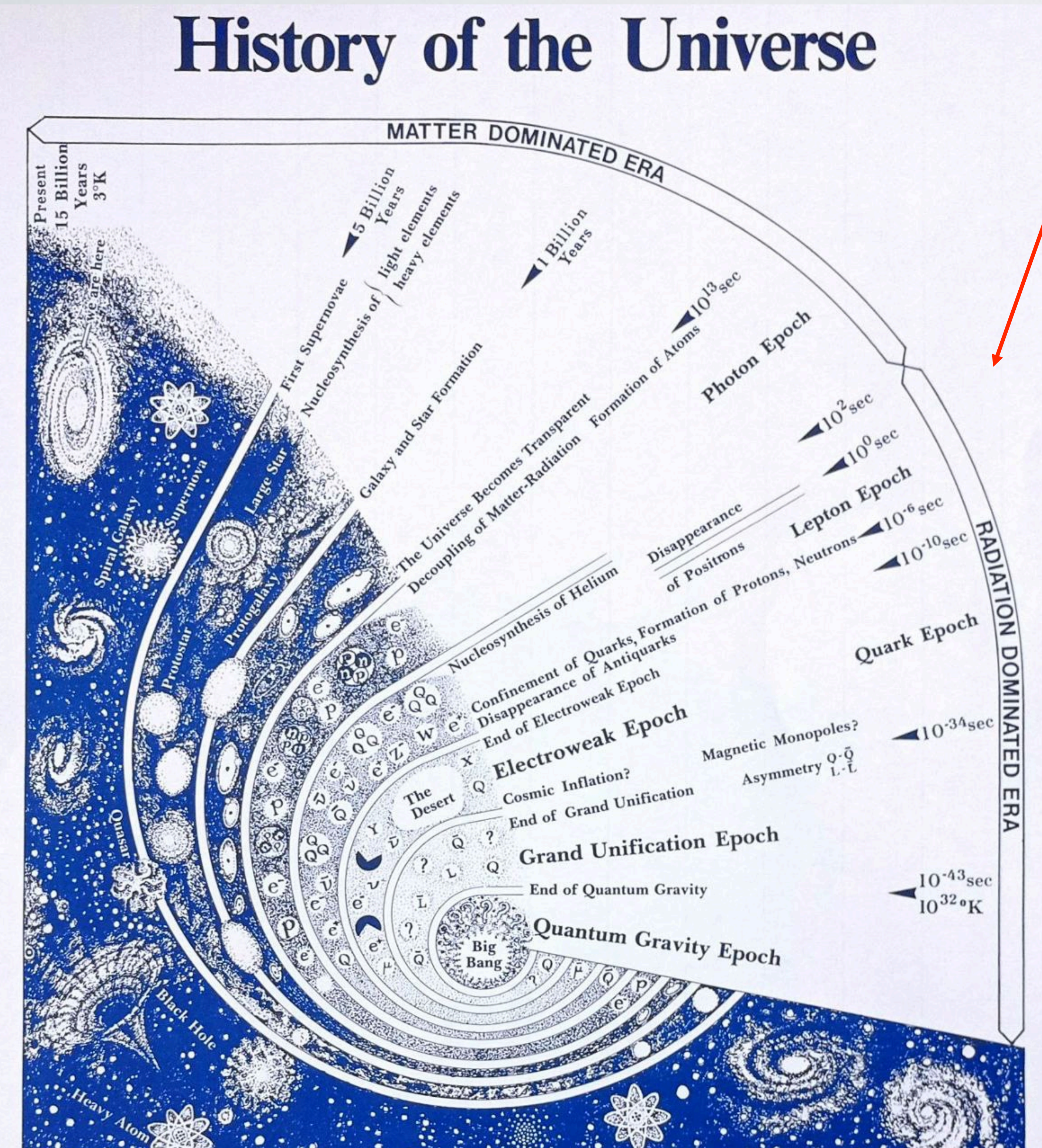
CMB: The oldest electromagnetic radiation in the universe



- 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
$(50 meV < m_{light} \simeq m_e or m_\tau)$

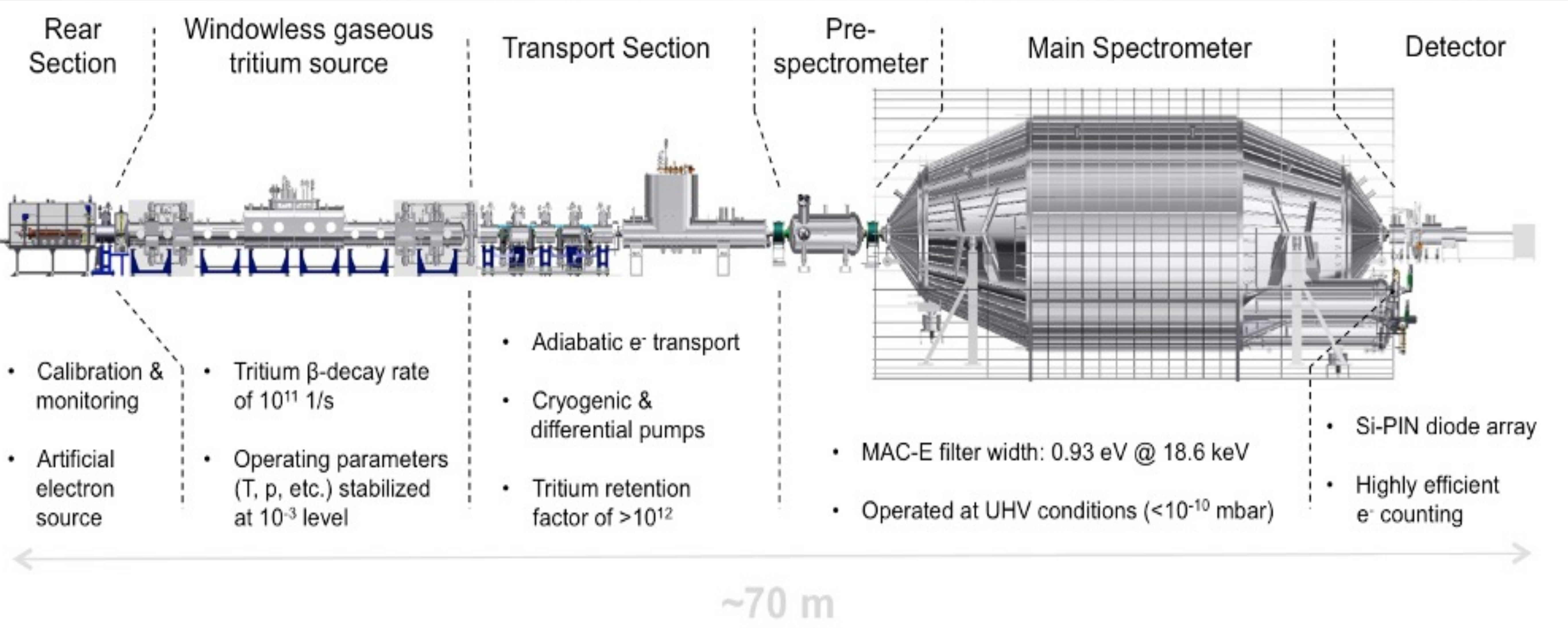
From Cosmology several limits at 95 % CL on Σm_ν from 0.56 to 0.11 eV

cosmic neutrino background
yet to be seen

WHERE WE ARE WITH DIRECT NEUTRINO MASS MEASUREMENT

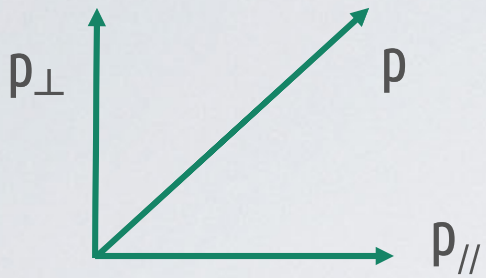
STRICTLY CONNECTED TO THE PTOLEMY GOAL

THE KATRIN EXPERIMENT



The **KA**rlsruhe **TRI**tium **N**eutrino experiment

MAC-E FILTER


p⊥
p
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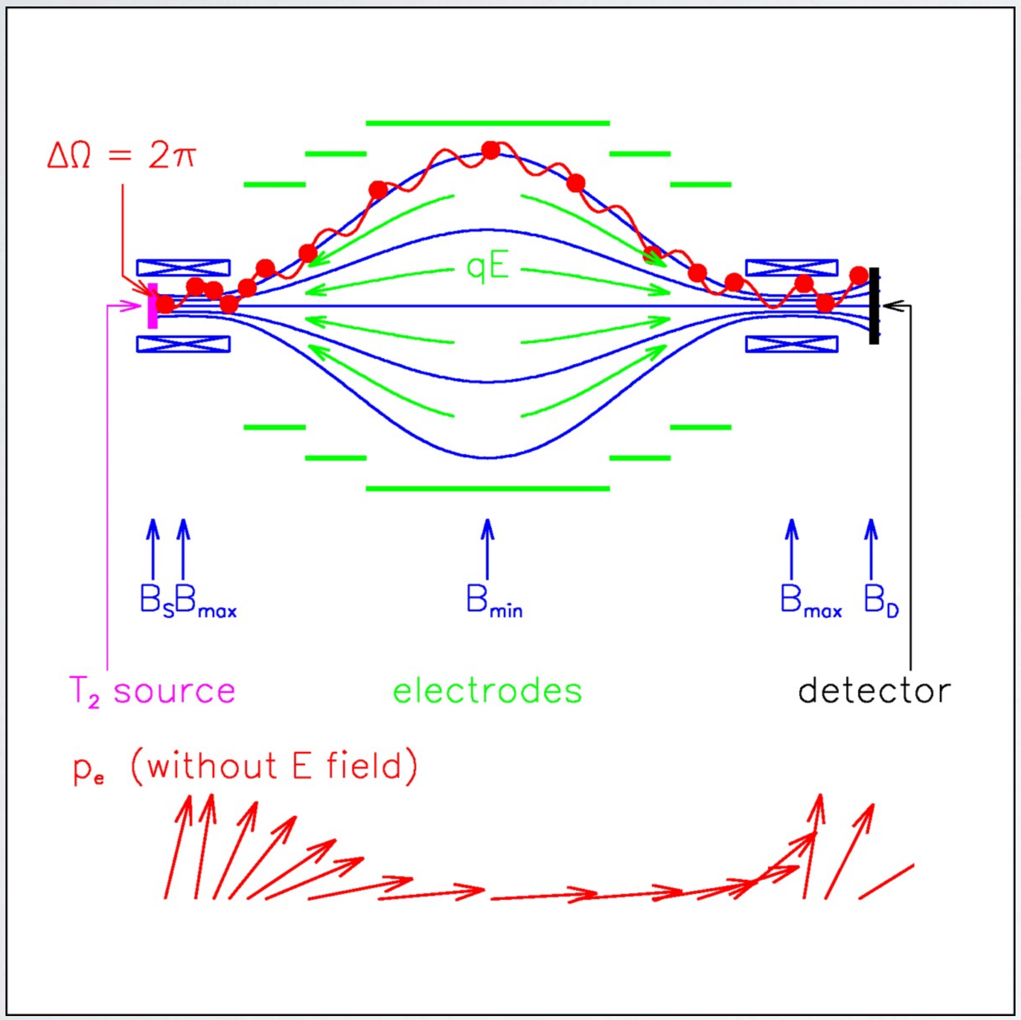
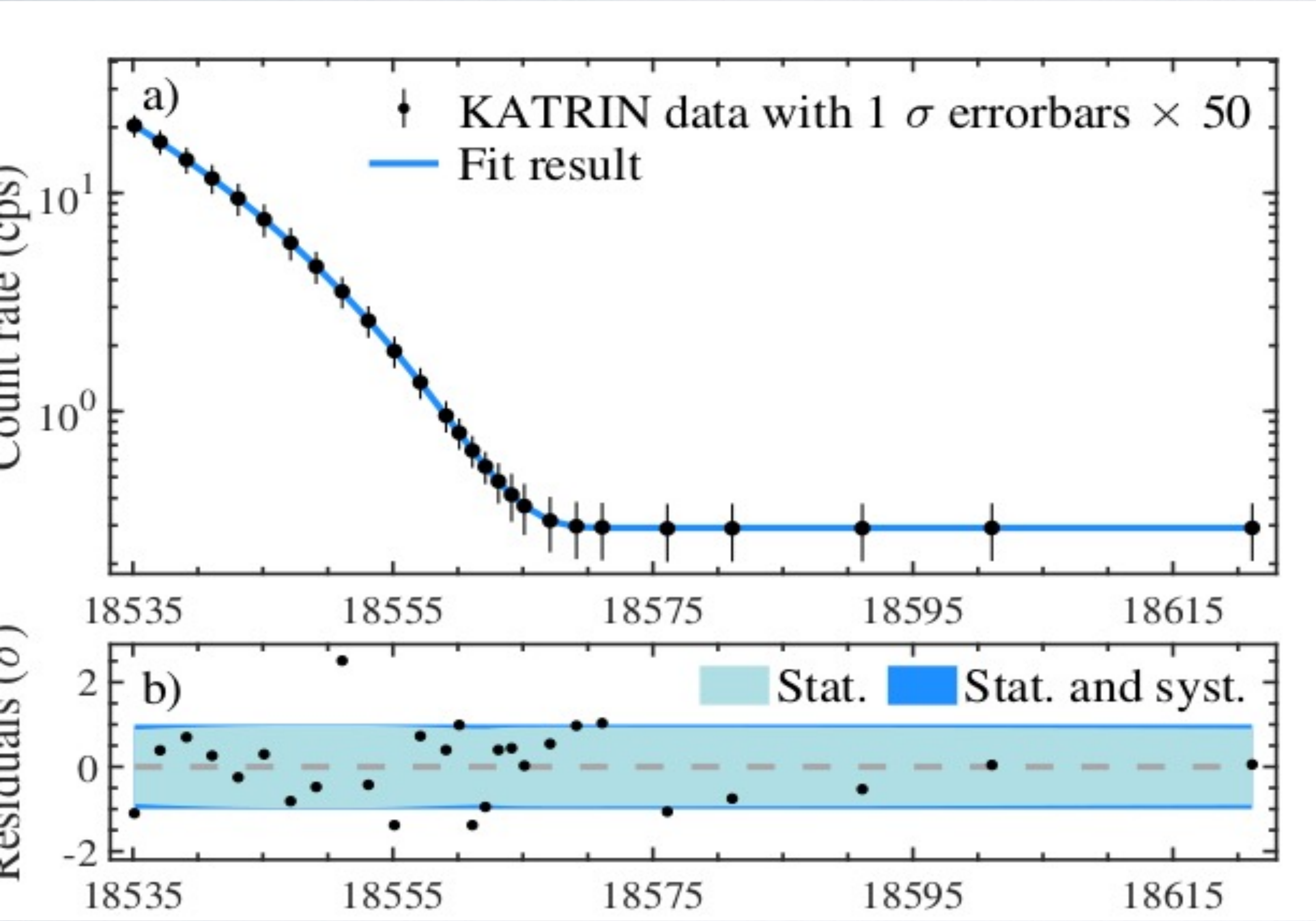

ΔΩ = 2π
qE
BS Bmax
Bmin
Bmax BD
T2 source
electrodes
detector
pe (without E field)

FEATURES AND RESULTS



Best experimental limit on neutrino mass

$m_e < 0.8$ eV (95% CL)
[Combined]

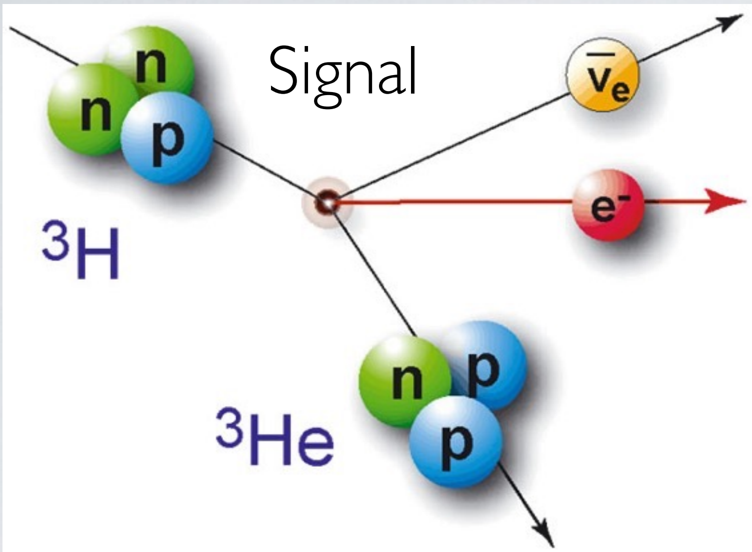
Sensitivity (5 years) ~ **0.2 eV** (limited)

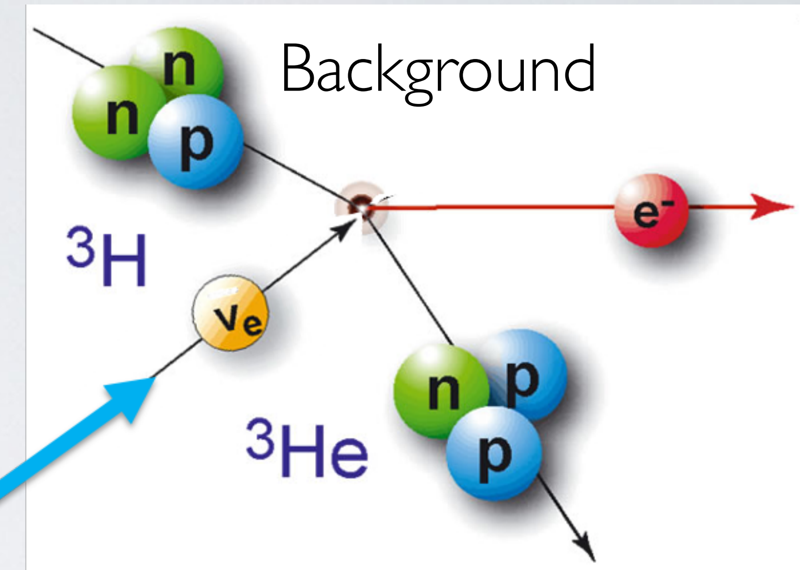
CNB target:
Gaseous target, **30 μg**
→ $3x10^{-6}$ events/year

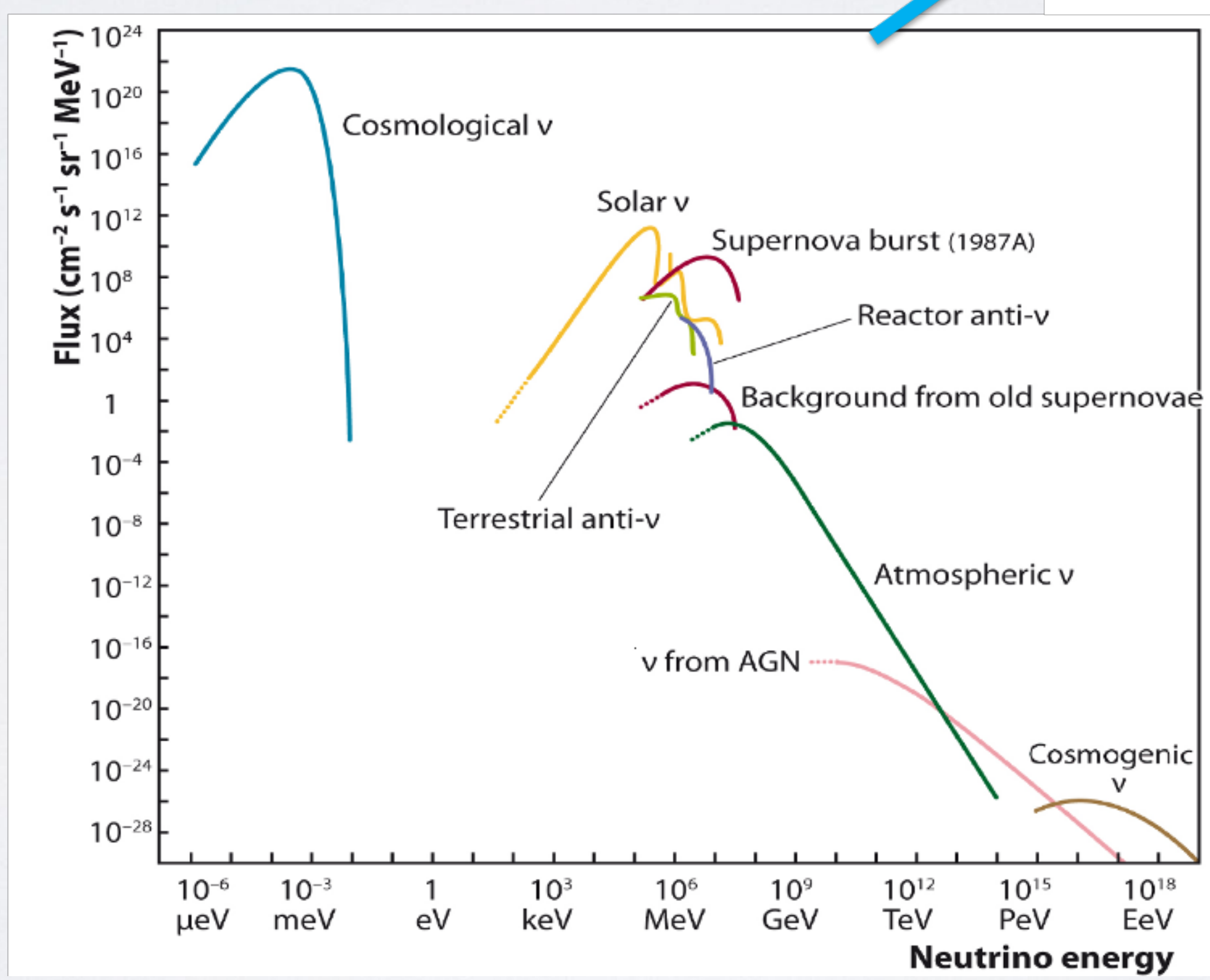
REQUIREMENTS FOR CNB DETECTION

- LARGE TARGET, 10 EVENTS/YEAR IF WE CONSIDER 100 G TARGET
- HIGH RATE (~10^{14} BQ) HANDLING
- FILTER COMPRESSION (~1M SIZE)
- HIGH RESOLUTION ELECTRON ENERGY MEASUREMENT (0.05 EV)
- VERY LOW TARGET INDUCED SMEARING

PTOLEMY - RELIC NEUTRINO DETECTION STRATEGY

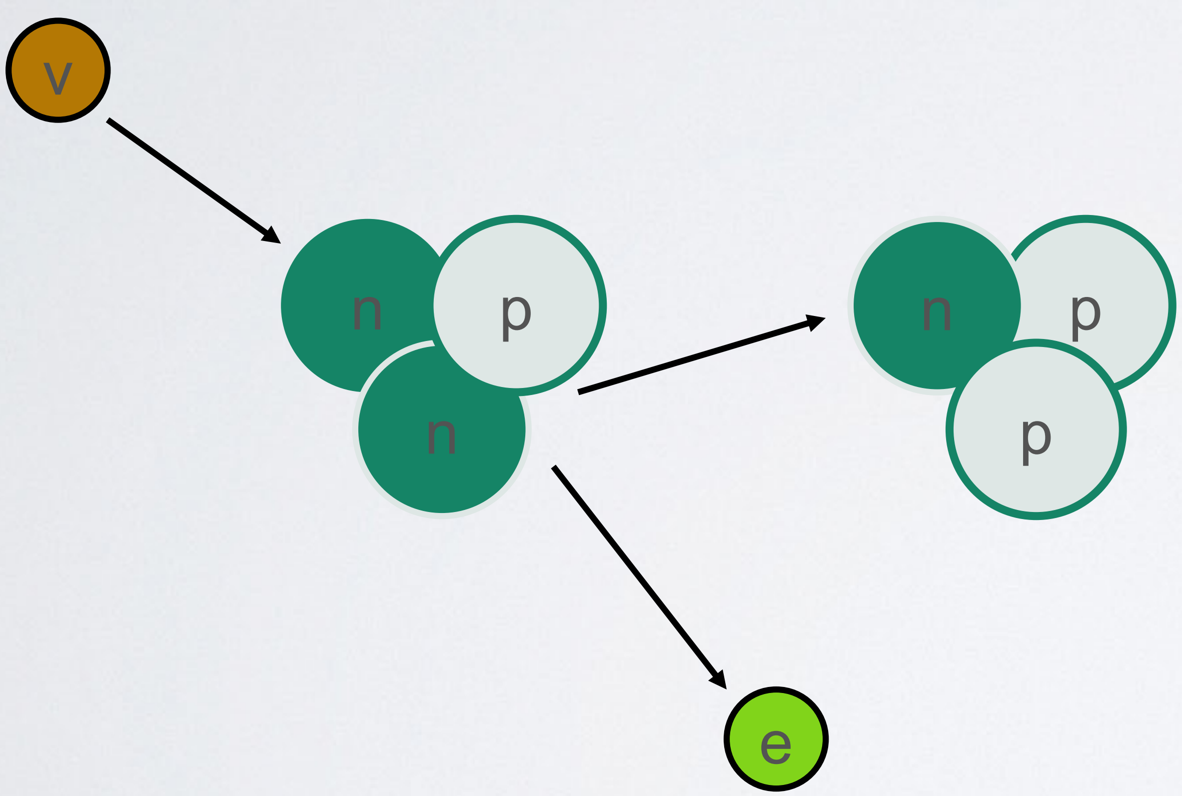


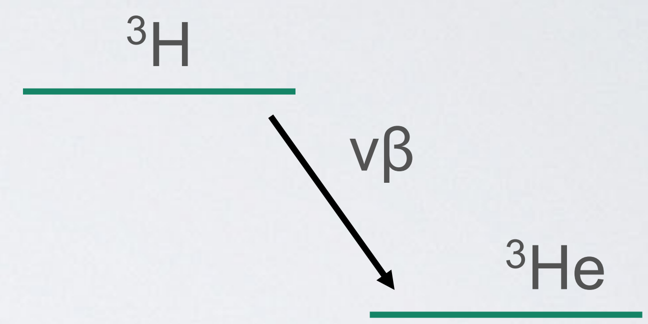


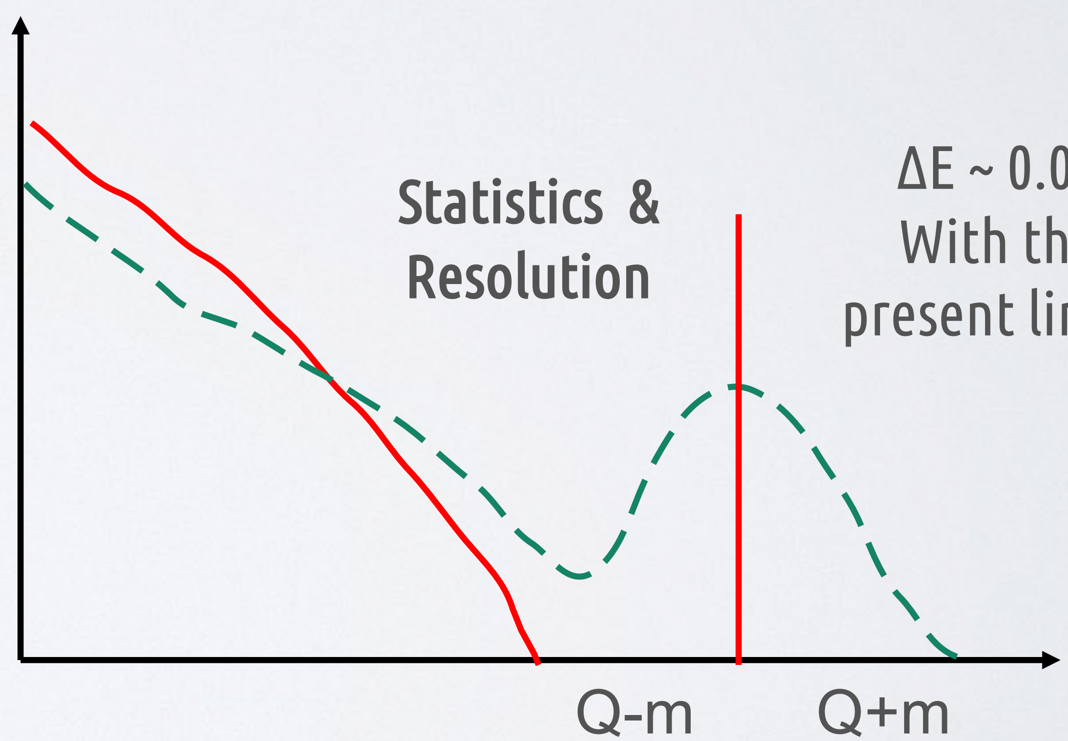


DETECTION PRINCIPLE – CNB ON ^{3}H

$$\nu_e + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^-$$



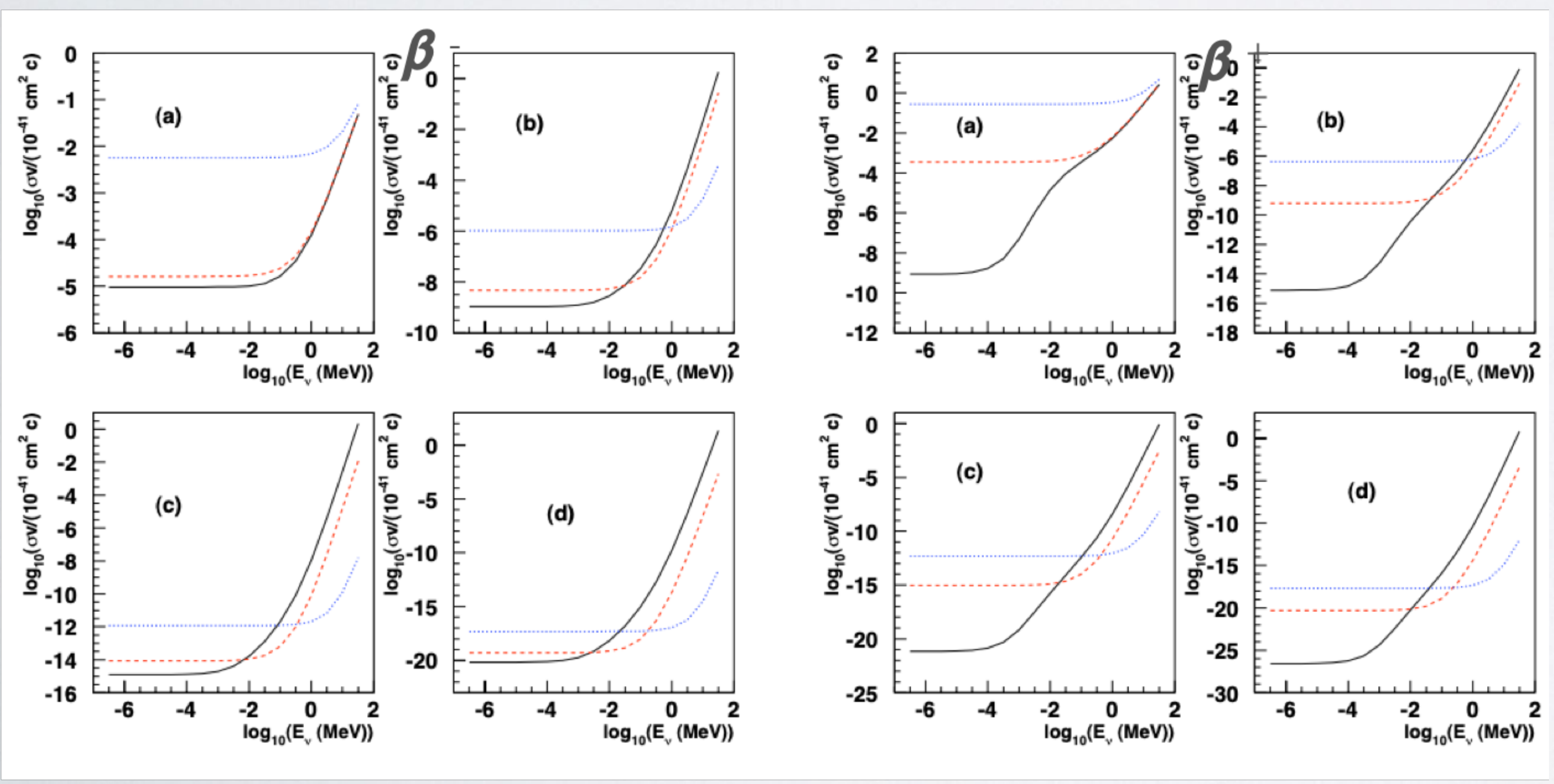




CROSS SECTION EVALUATION

Tritium has the largest product of capture cross section and lifetime

$$^3\text{H} \rightarrow {}^3\text{He}^+ + e^- + \bar{\nu}_e \qquad (Q \simeq 18.6\ \text{keV})$$
$$\nu_e + {}^3\text{H} \rightarrow {}^3\text{He}^+ + e^-$$

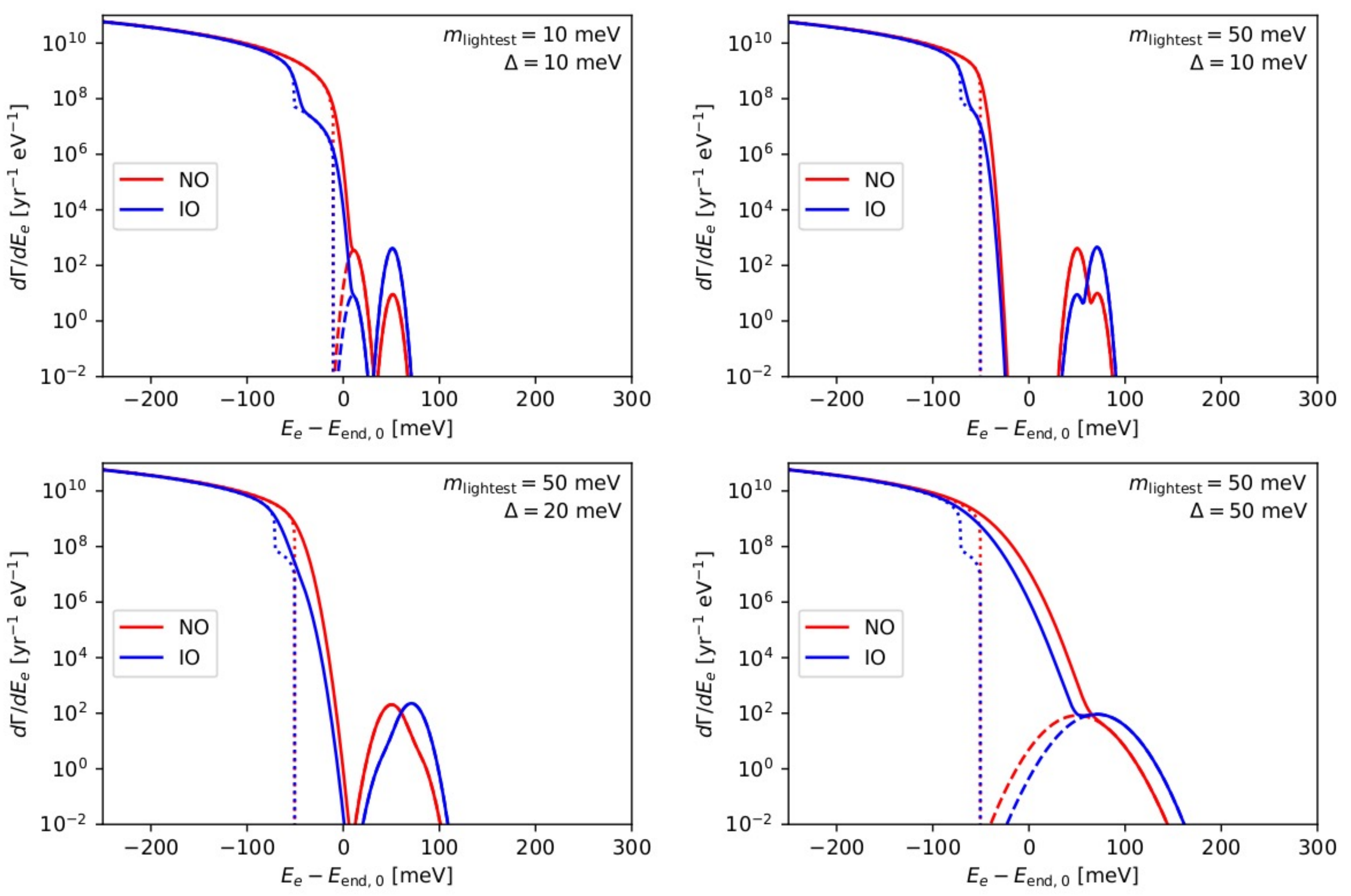


Detailed evaluation on 2007
JCAP 06 (2007) 015
of $\sigma \times \tau$ renewed the dormant discussion on relic neutrino detection and paved the view to a possible experiment.
Several authors confirmed the cross-section evaluation and added information:

R Lazauskas, P Vogel, C Volpe ,
J. Phys. G: Nucl. Part. Phys. 35 025001,
AJ Long, C Lunardini, *JCAP 08 (2014) 038*

On 1962 S. Weinberg discussed the relic neutrino detection in a different physics framework, where Pauli suppression would deform the end-point of the electron spectrum.

PRACTICAL EXAMPLES

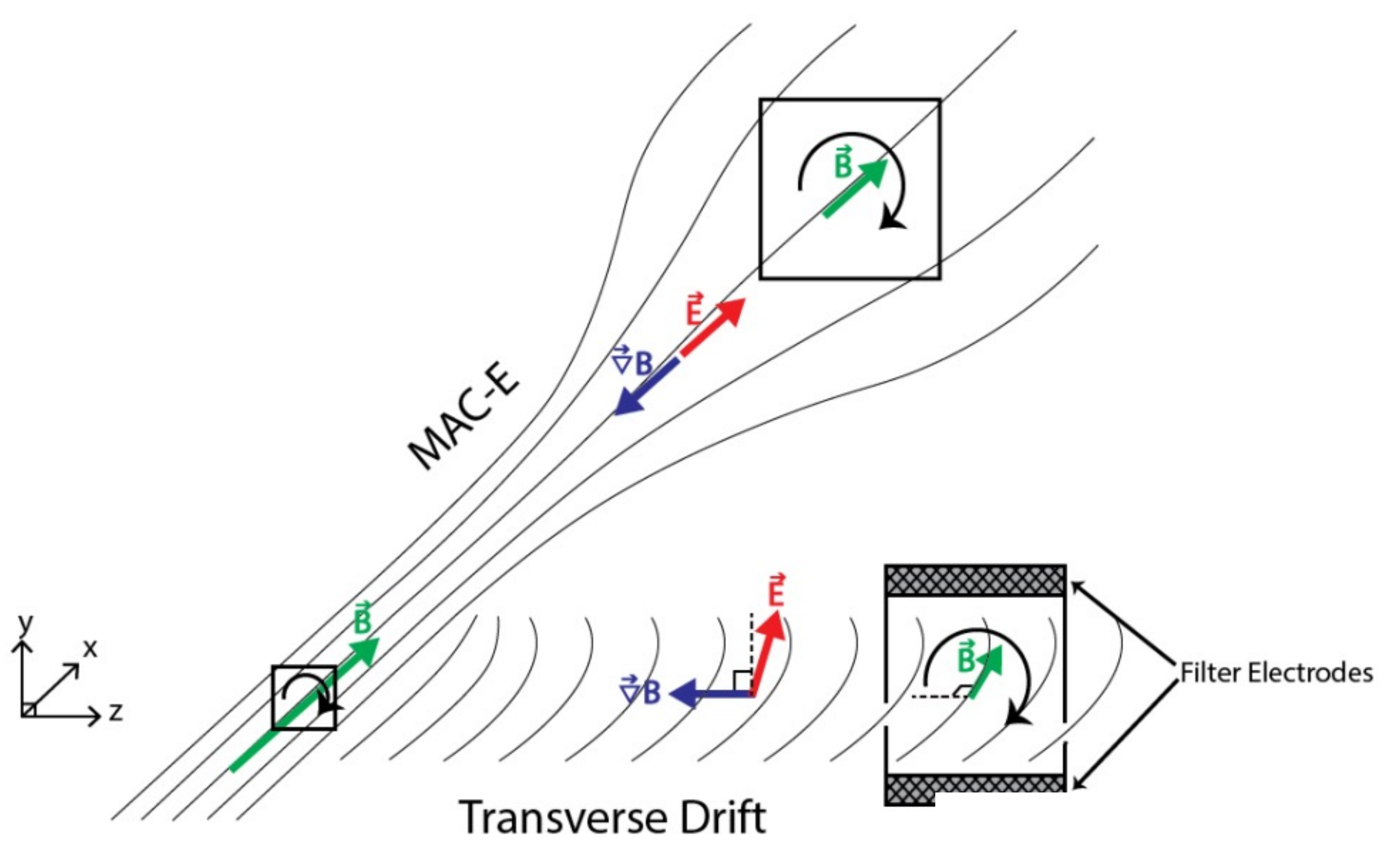


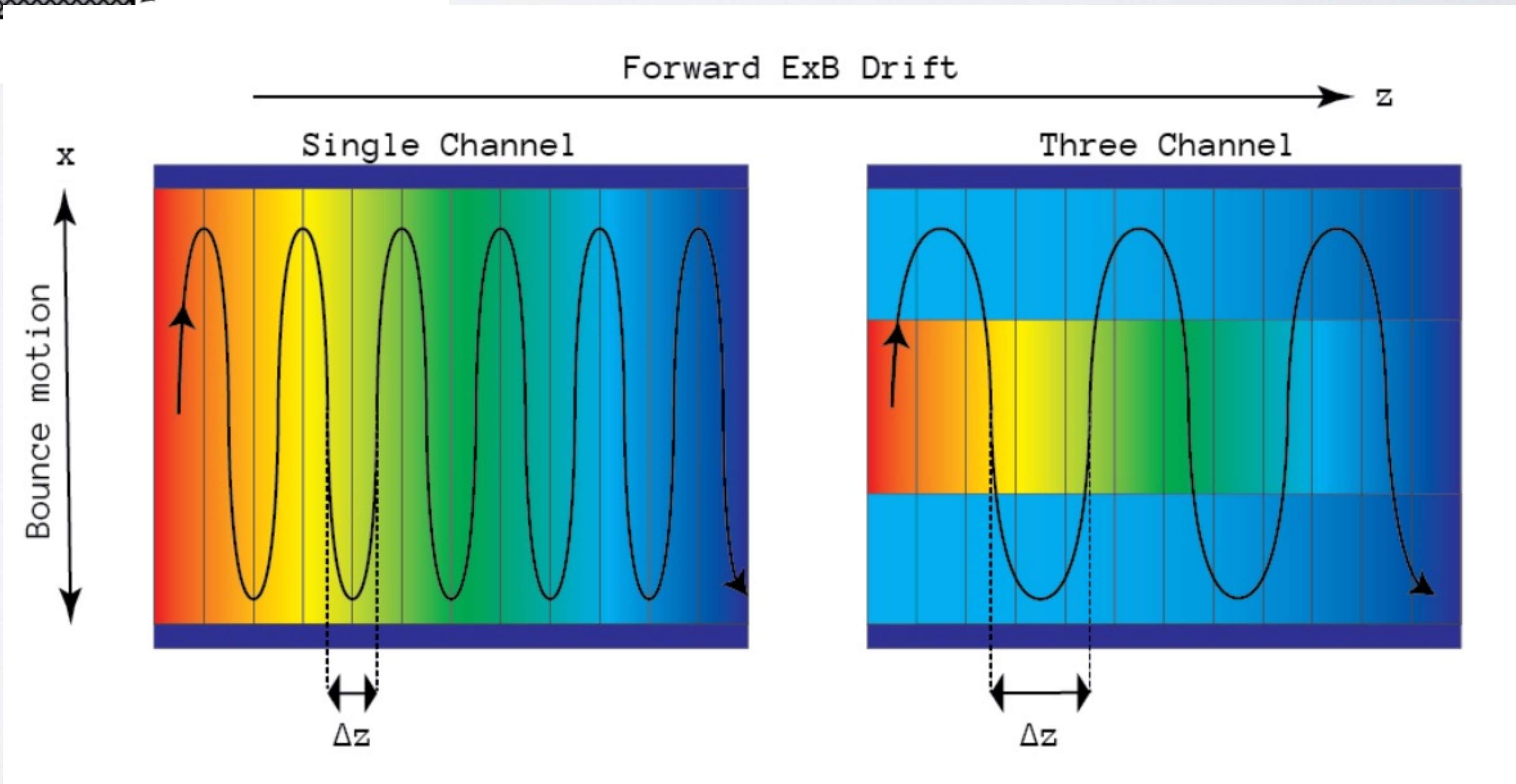
M.G. Betti et al., 2019

A NEW FILTER CONCEPT IS NEEDED

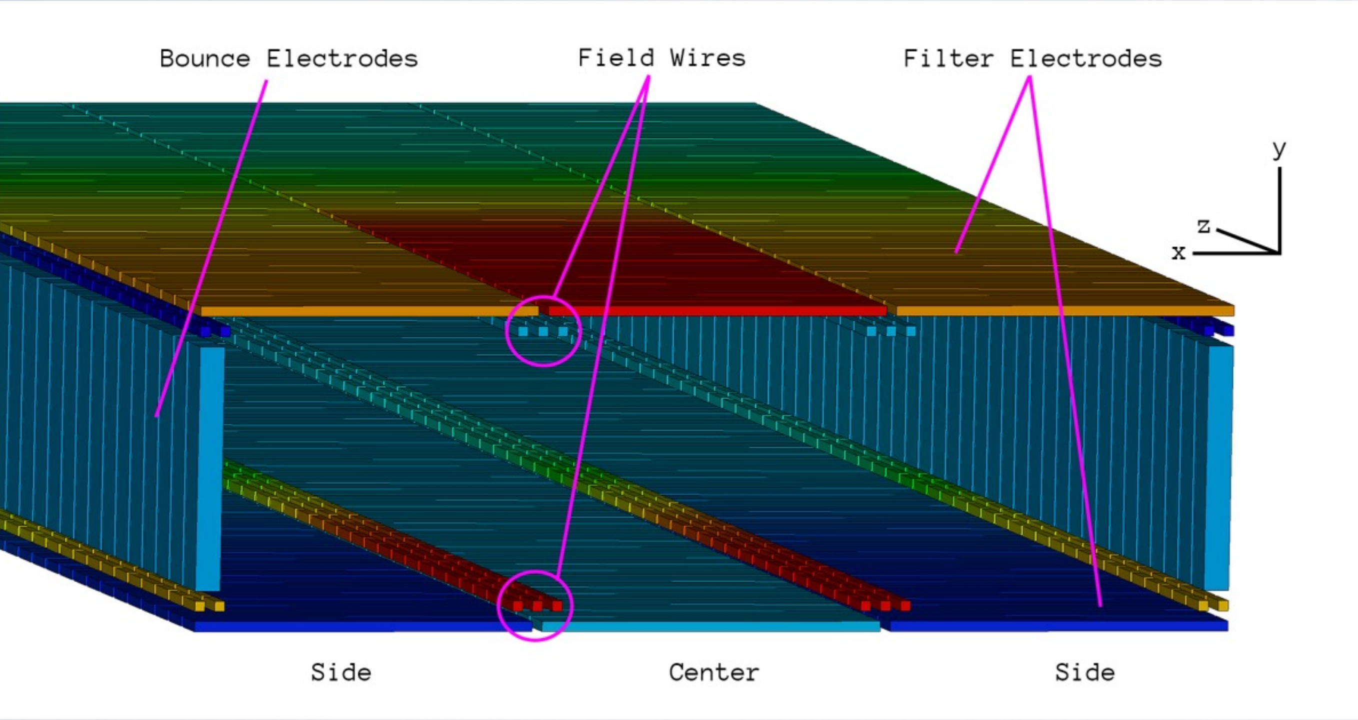
KATRIN -> POTLEMY filter

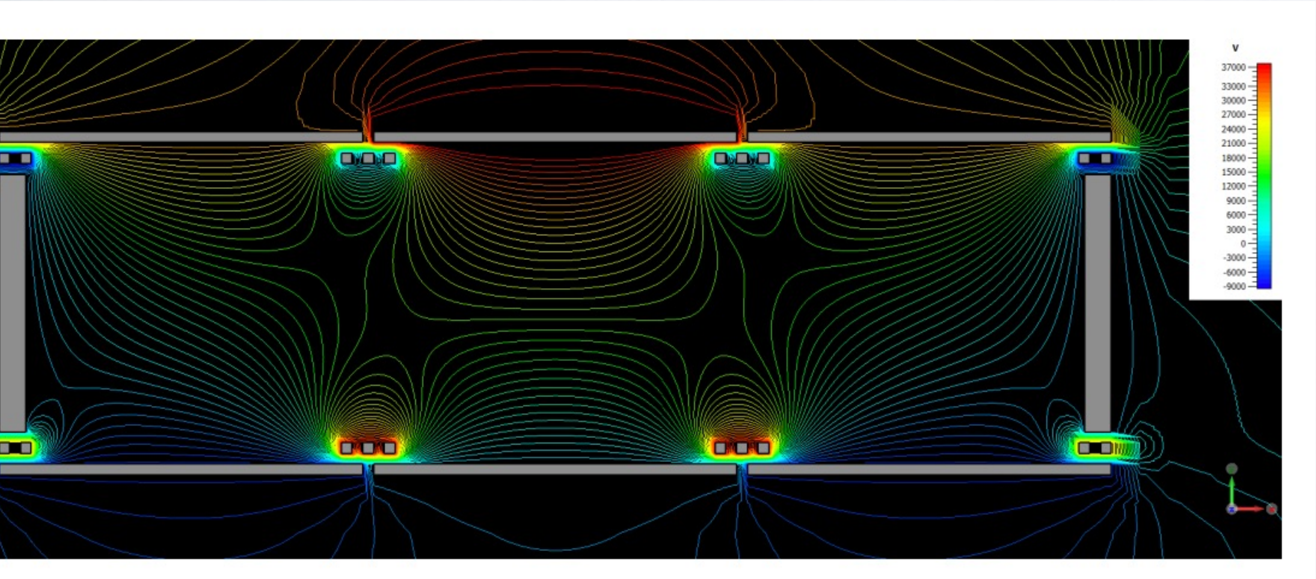
B moves from the E direction to the perpendicular one.

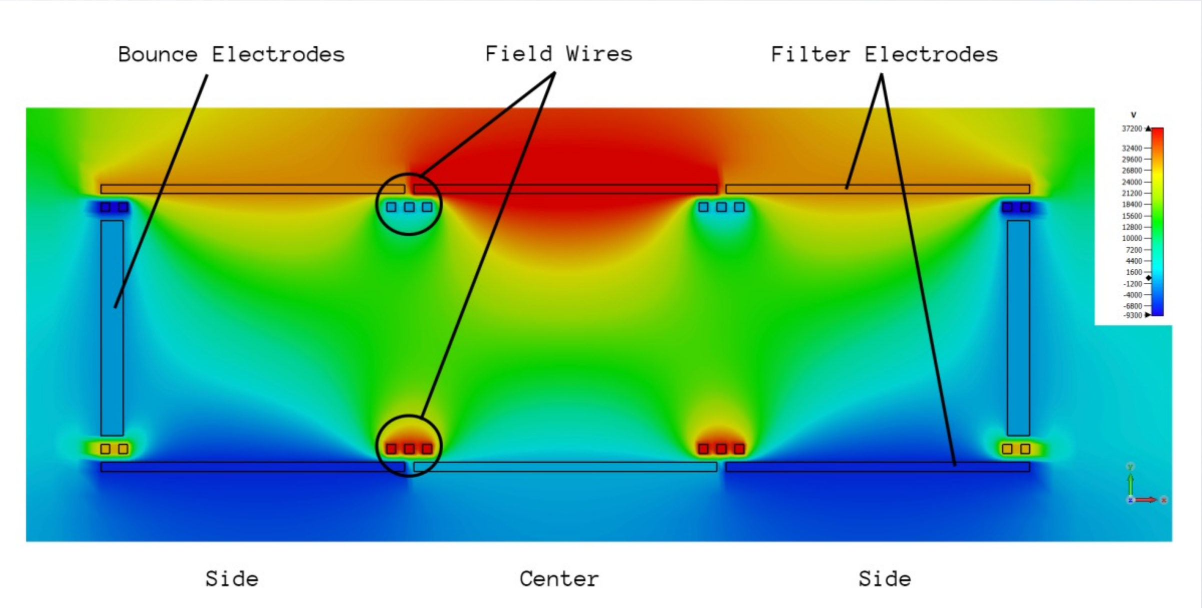




Three channels well simulation







THE PTOLEMY PROJECT

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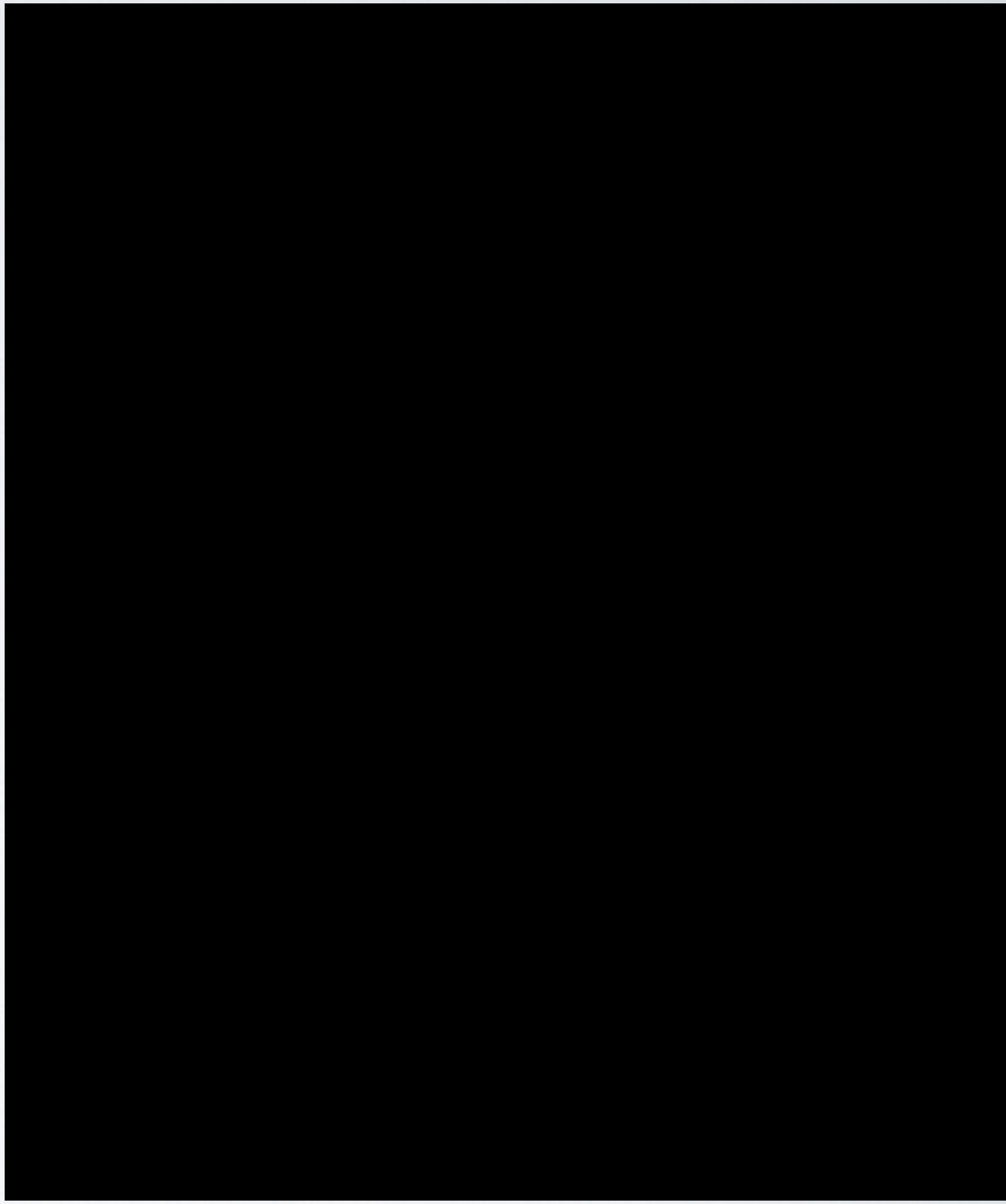
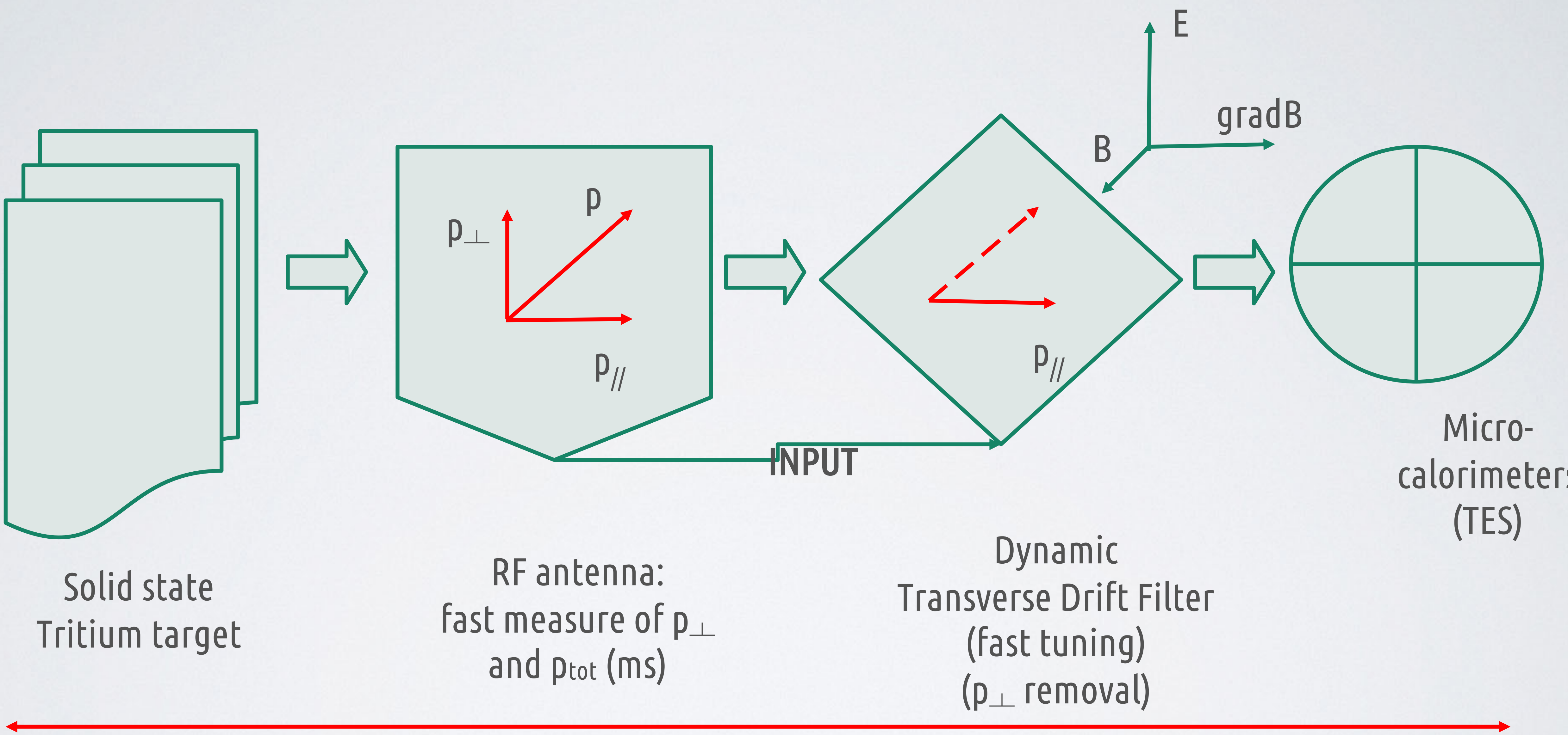
[M.G. Betti et al., 2019]
JINST 17 (2022) 05, P05021



DETECTOR CONCEPT

IN BLOCKS

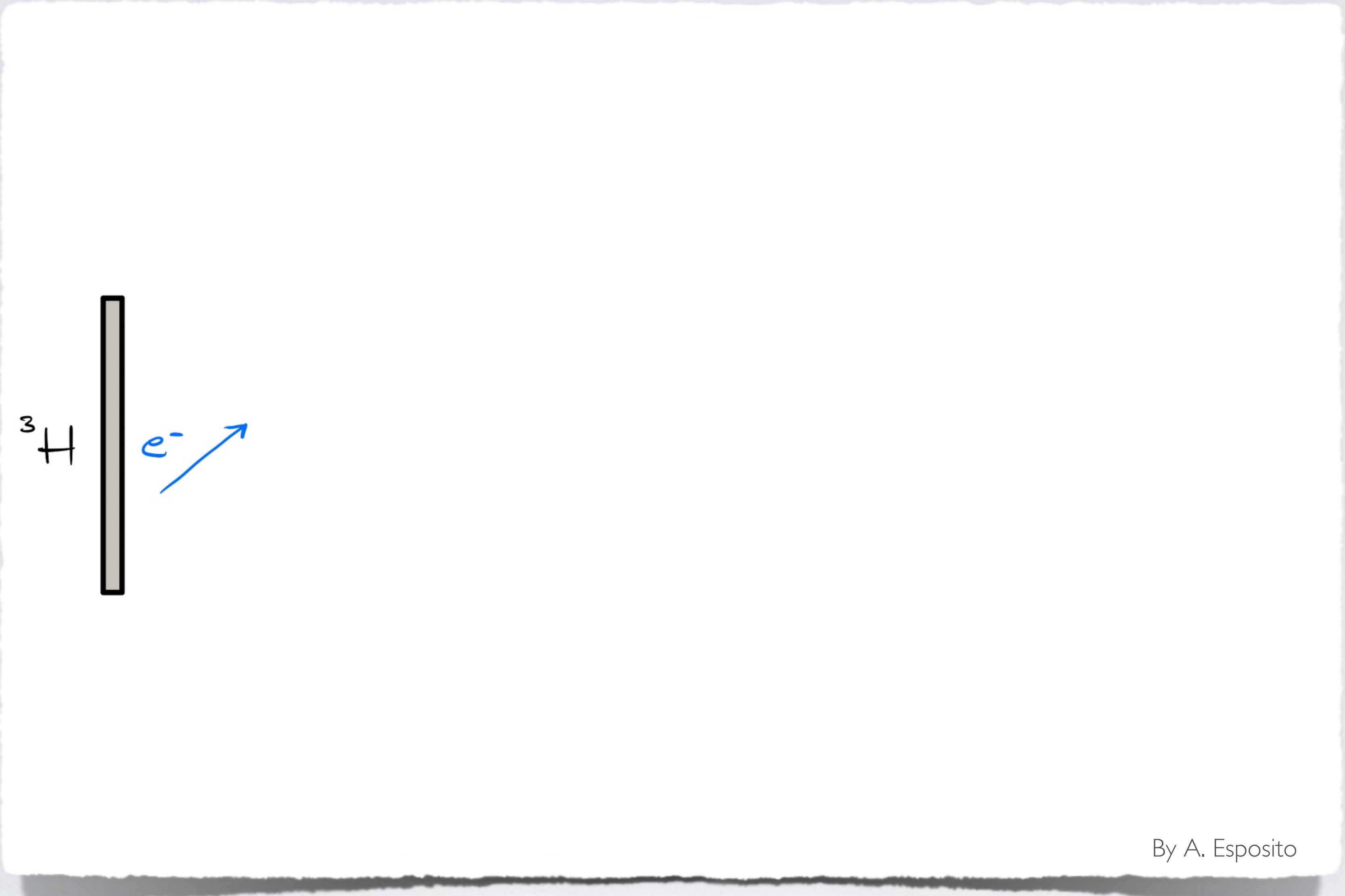


$$E_{tot} = q(V_{TES} - V_{target}) + E_{TES} + E_{RF\,corr}$$

PTOLEMY: THE IDEA

JINST 17 (2022) 05, P05021

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



PTOLEMY: THE IDEA

JINST 17 (2022) 05, P05021

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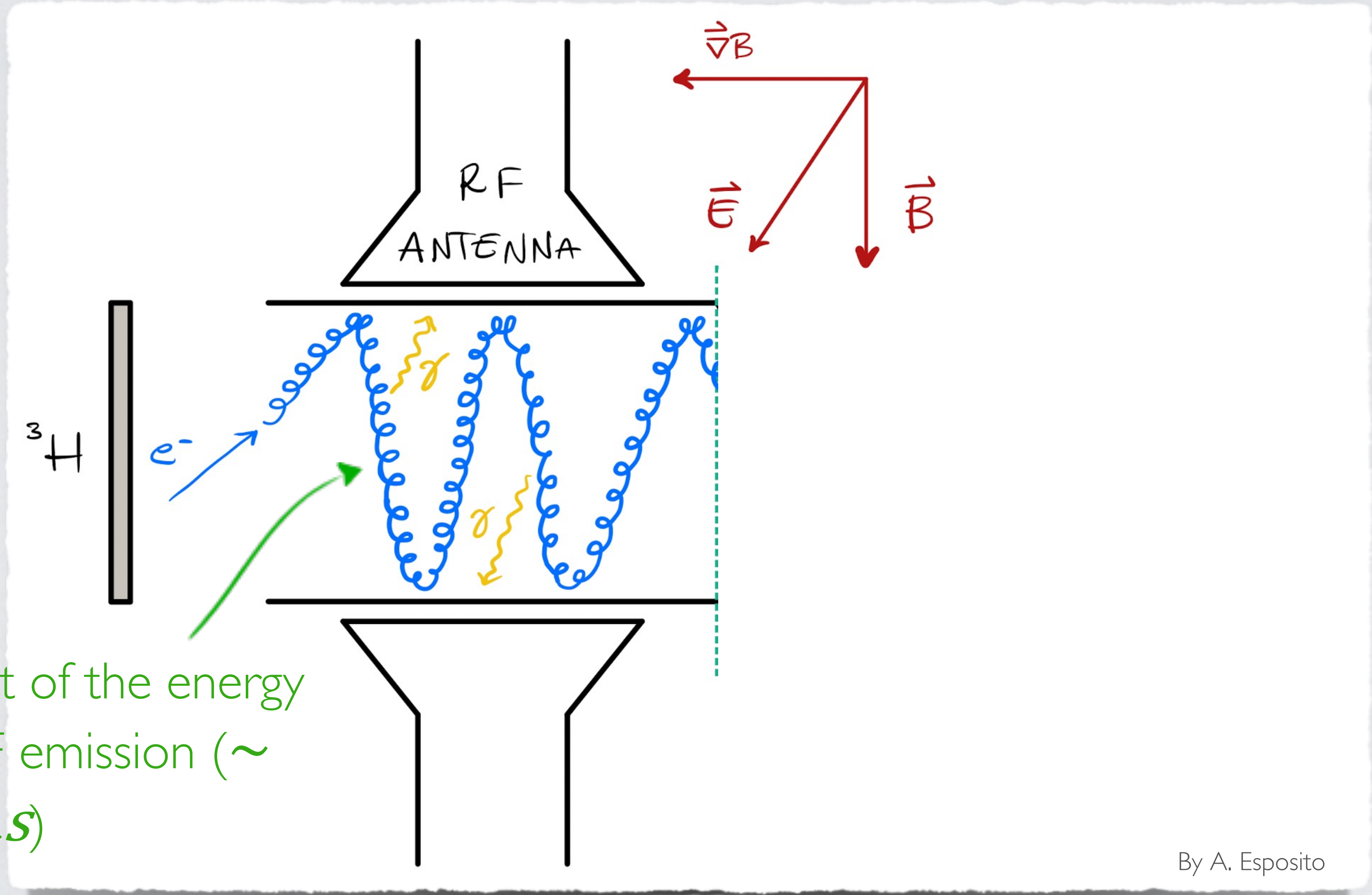

first measurement of the energy via cyclotron RF emission ($\sim 10\mu s$)

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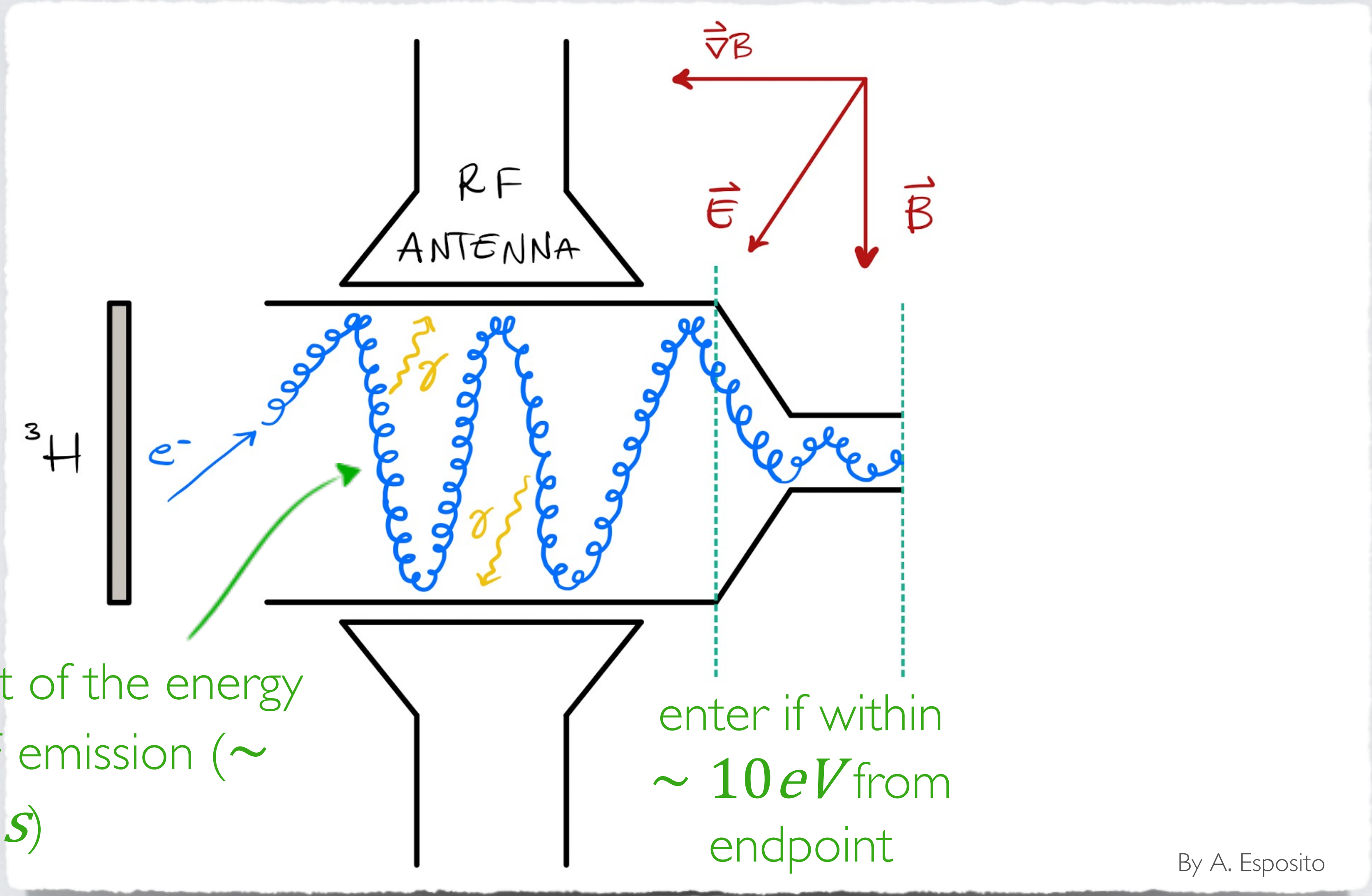


first measurement of the energy via cyclotron RF emission ($\sim 10\mu s$)

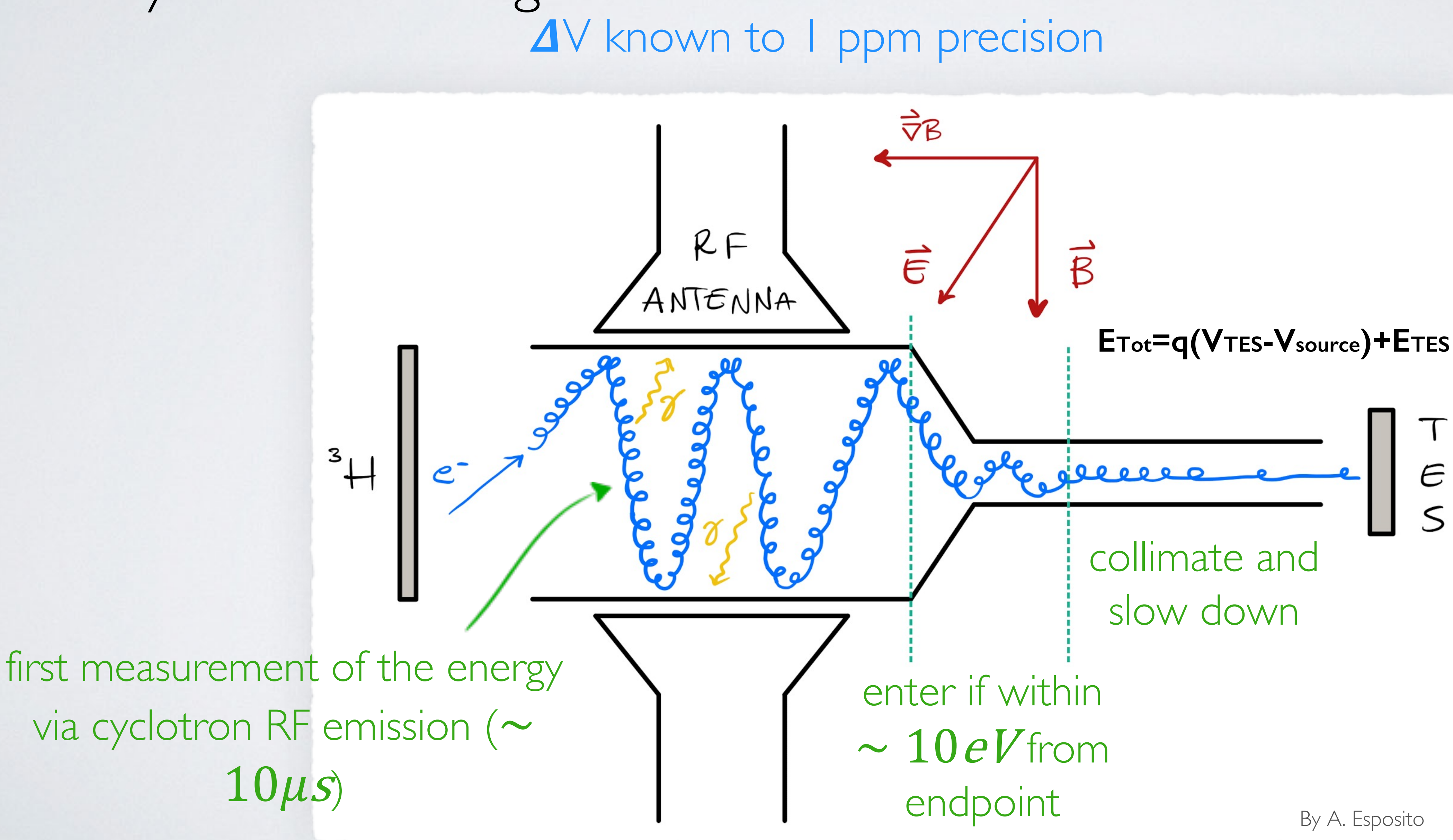
enter if within $\sim 10eV$ from endpoint

By A. Esposito

PTOLEMY: THE IDEA

JINST 17 (2022) 05, P05021

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



DETECTOR CONCEPT

SIMULATION WITH CST SOFTWARE

$$V_D = \left(qE + F - \mu\nabla B - m\frac{dV}{dt}\right)\times m\frac{B}{qB^2}$$

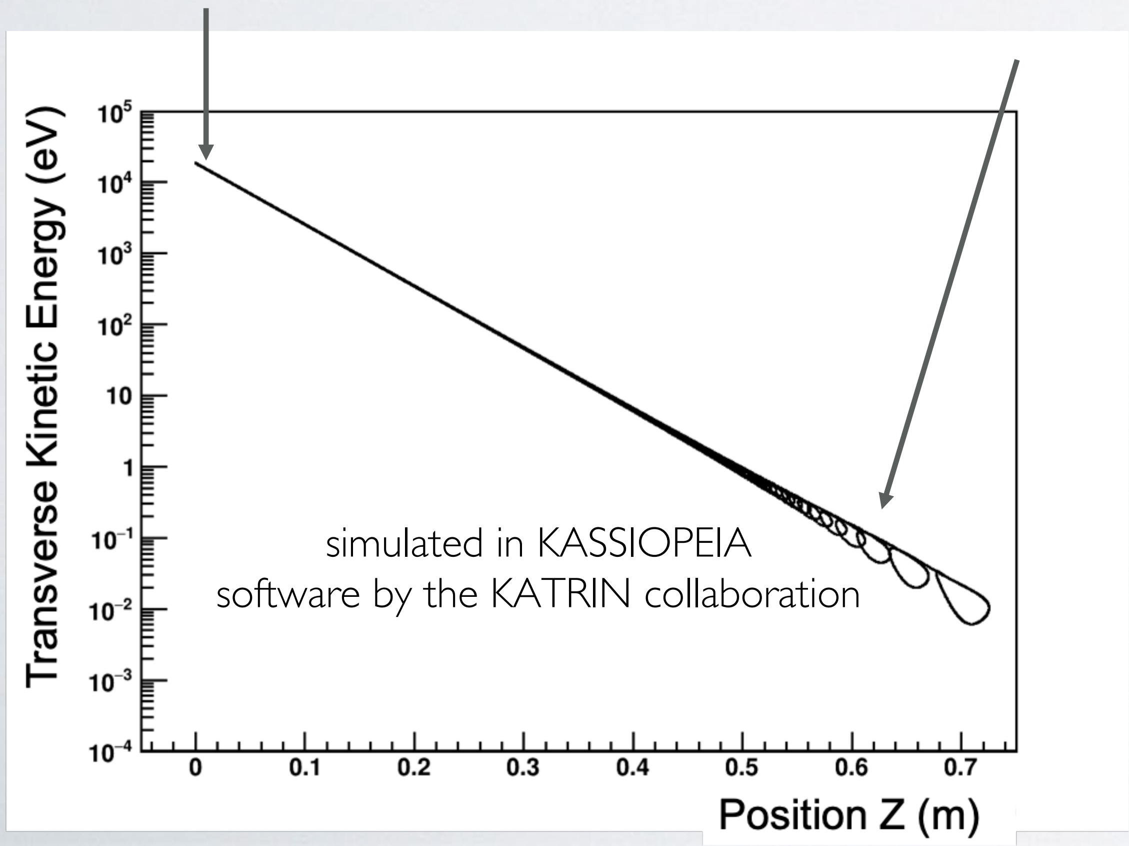
$$\frac{dT_\perp}{dt} = \frac{\mu}{B^2}\boldsymbol{E}\cdot(\boldsymbol{\nabla}B\times\boldsymbol{B})$$

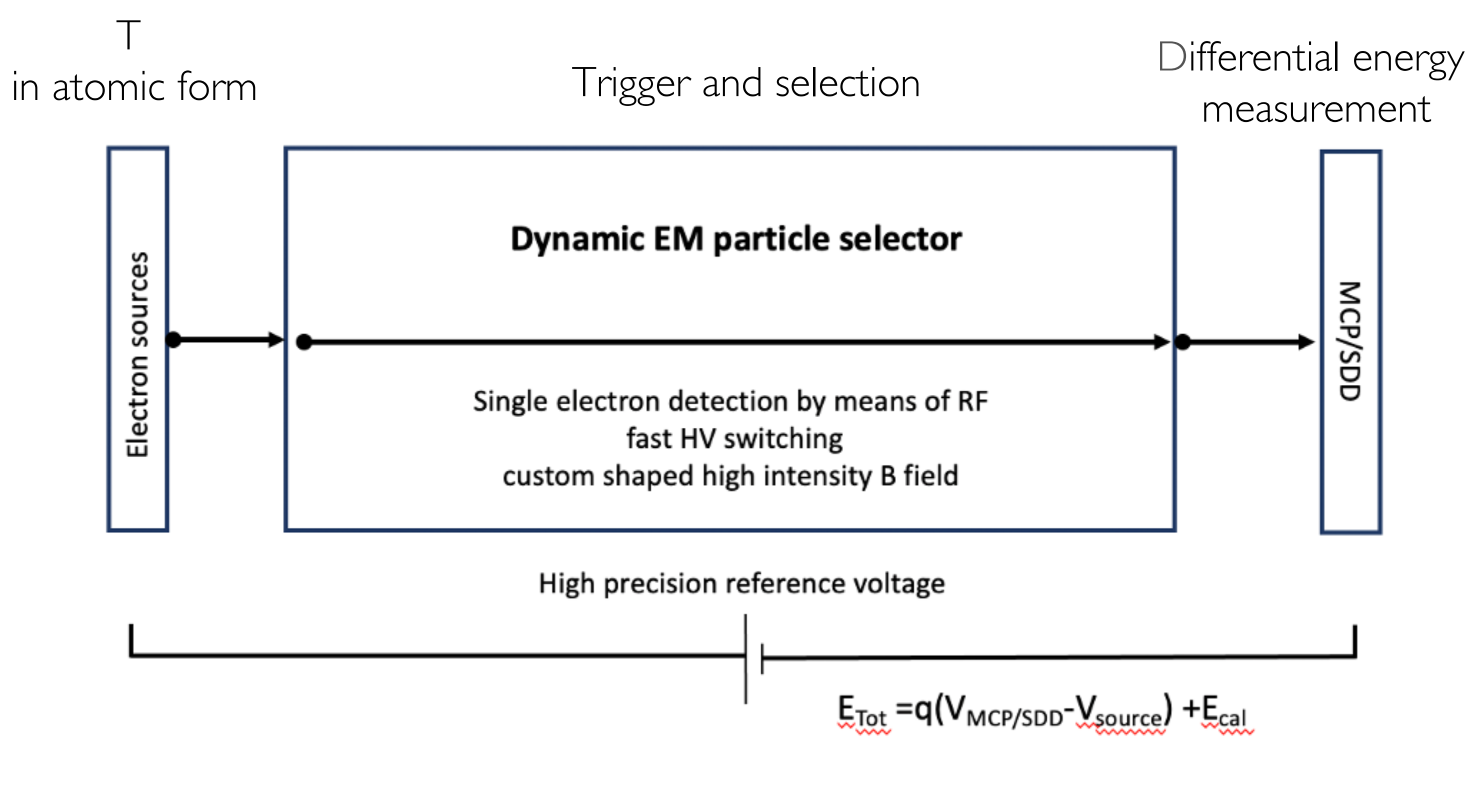
Prog.Part.Nucl.Phys. 106 (2019) 120-131

JINST 17 (2022) 05, P05021

New concept: **Transverse drift filter**

18.6 keV ➡ 0.01 keV in 0.7 meters

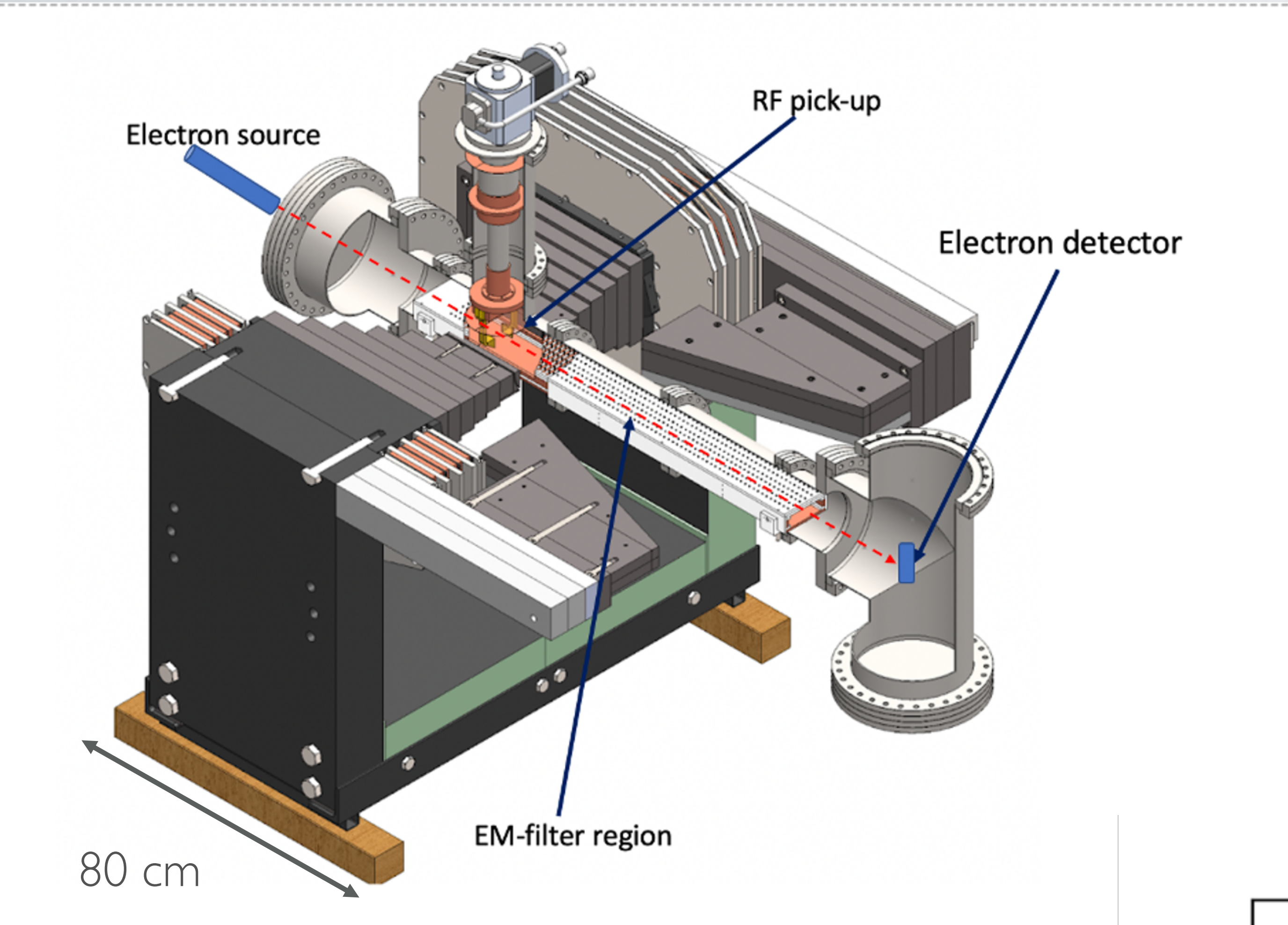


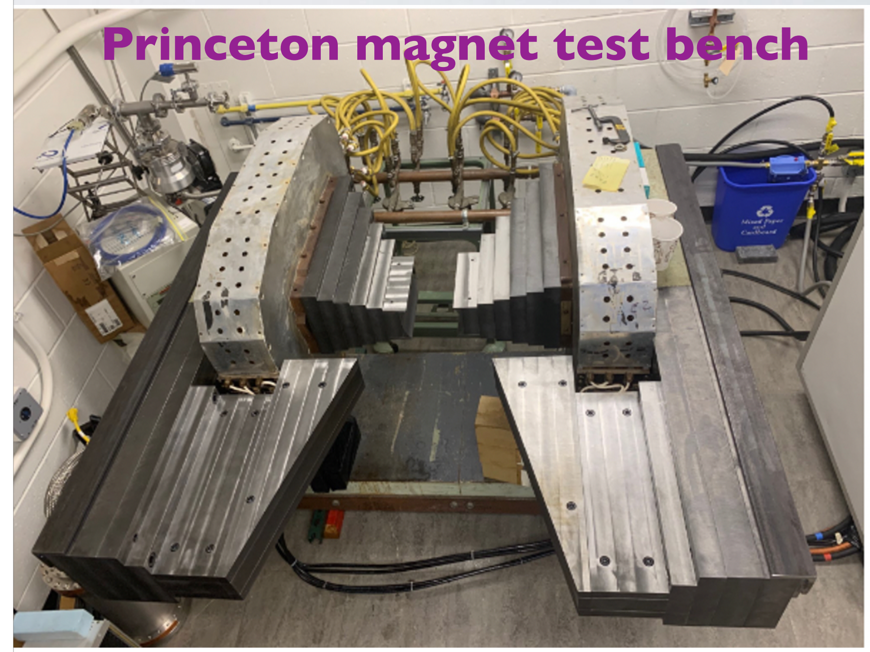


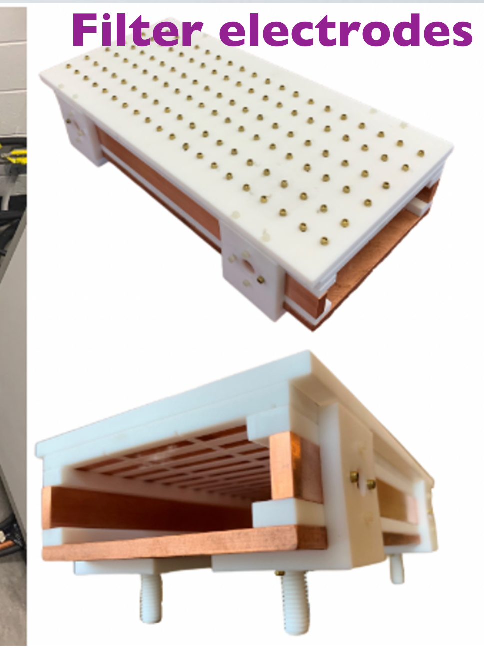
- PTOLEMY aims at using TES detectors with an envisaged resolution of $\Delta E \simeq 0.05eV$
- However:
  1. TES' perform best with energies $O(10eV)$ need to slow the electrons down
  2. TES' are slow response detectors need to reduce the number of electrons coming from β-decay

DEMONSTRATOR MAGNET

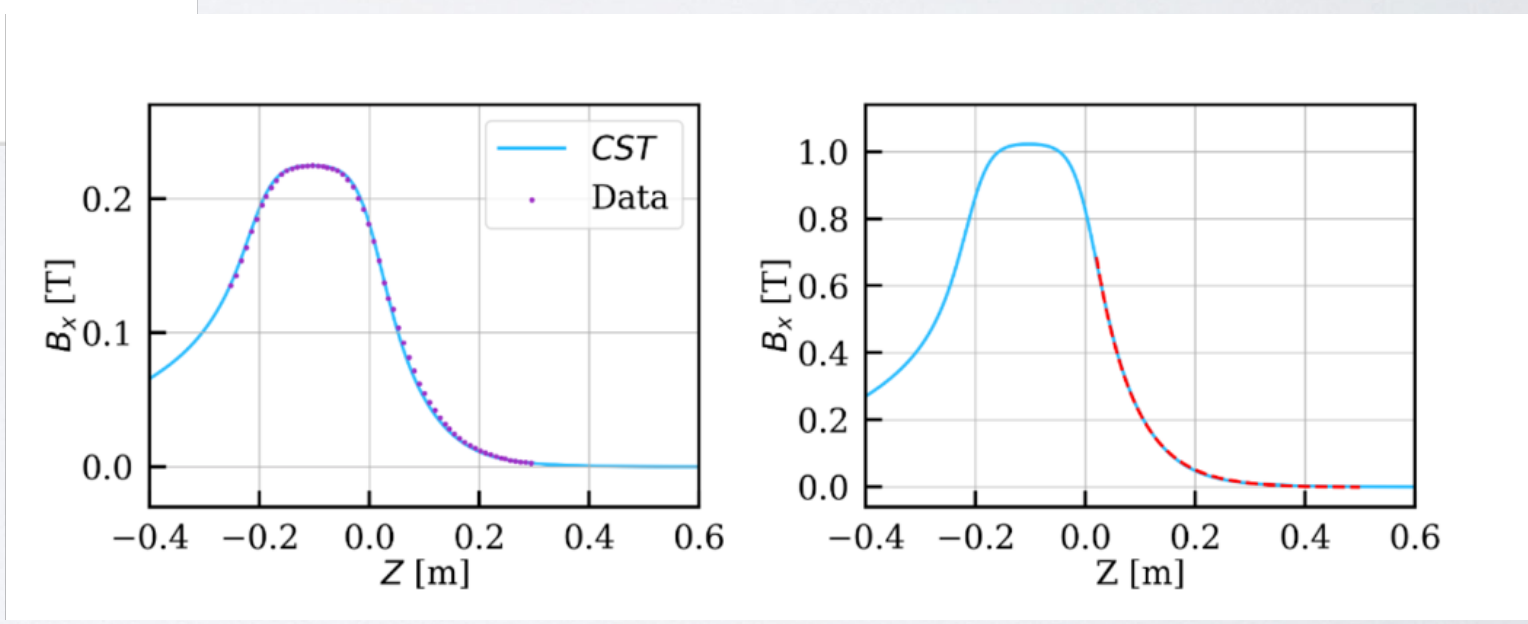
BEING REBUILT AT LNGS IN A LARGER SIZE.



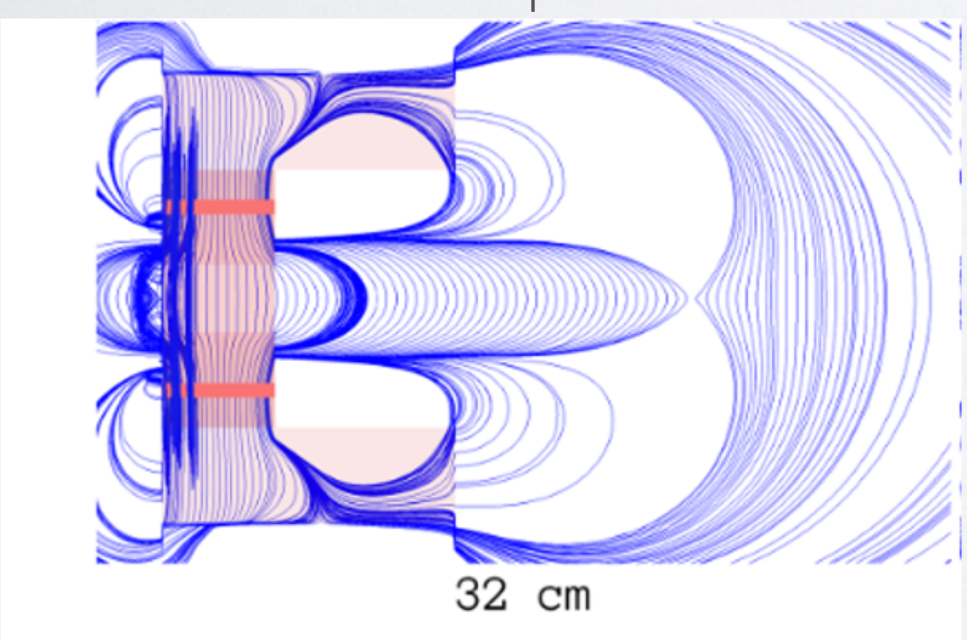




Measured B field shape as expected

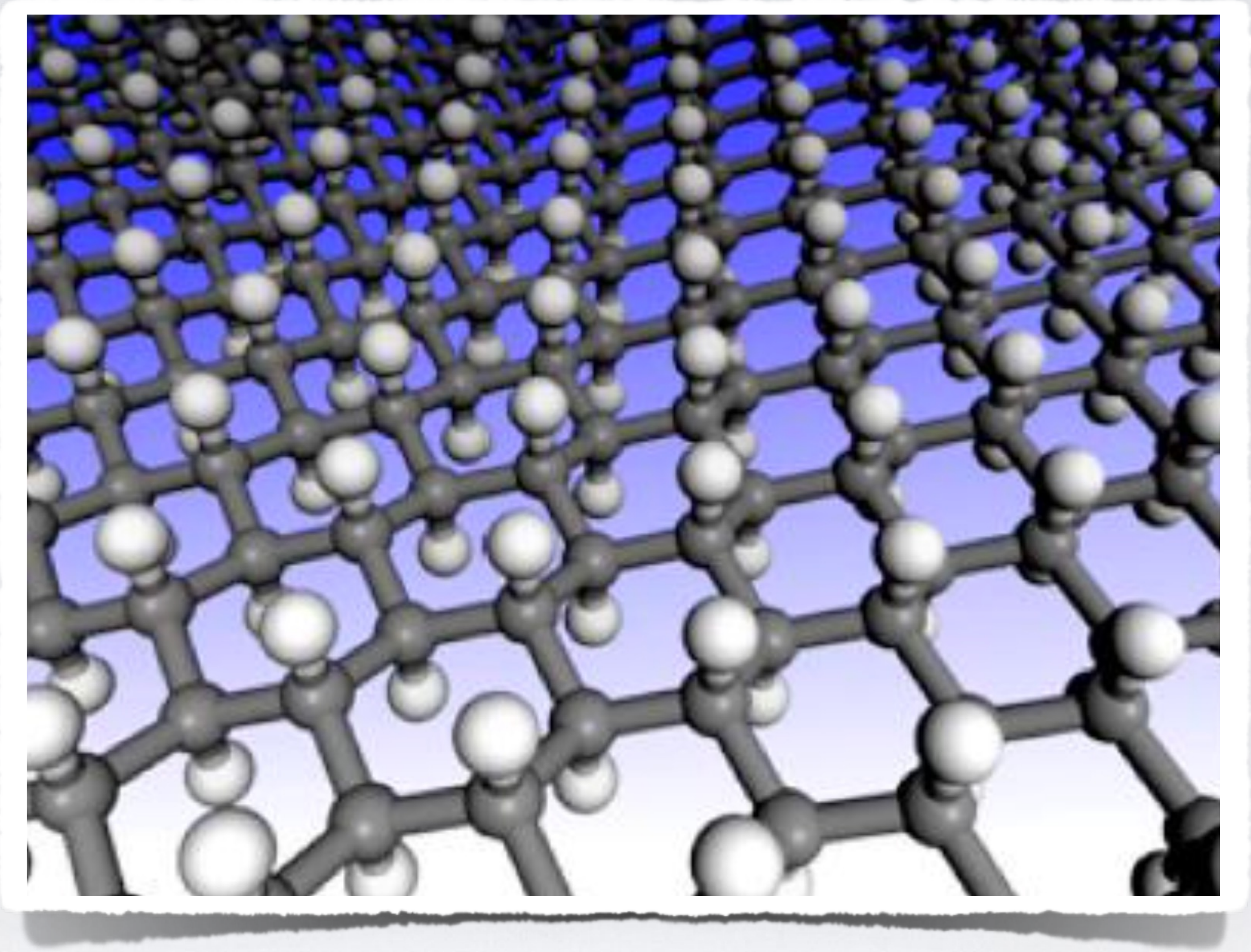


Simulated B-map



PTOLEMY: ATOMIC T TARGET

- PTOLEMY has to deal with large instrumented mass. Distribute atomic tritium on a solid state substrate (e.g. graphene)



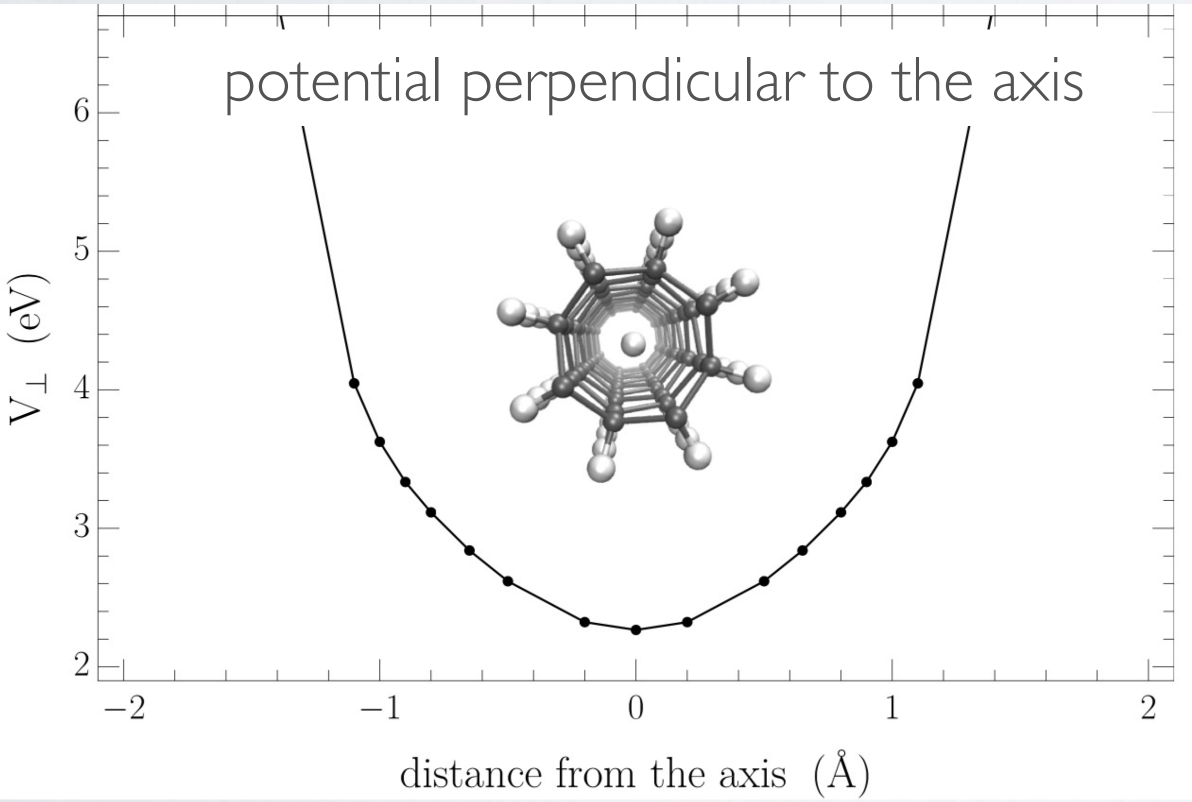
90% H loading demonstrated in the framework of the PTOLEMY R&D by Rome group (unprecedented value).
[see Betti et al. – Nano Lett. 2022]

ALTERNATIVES

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

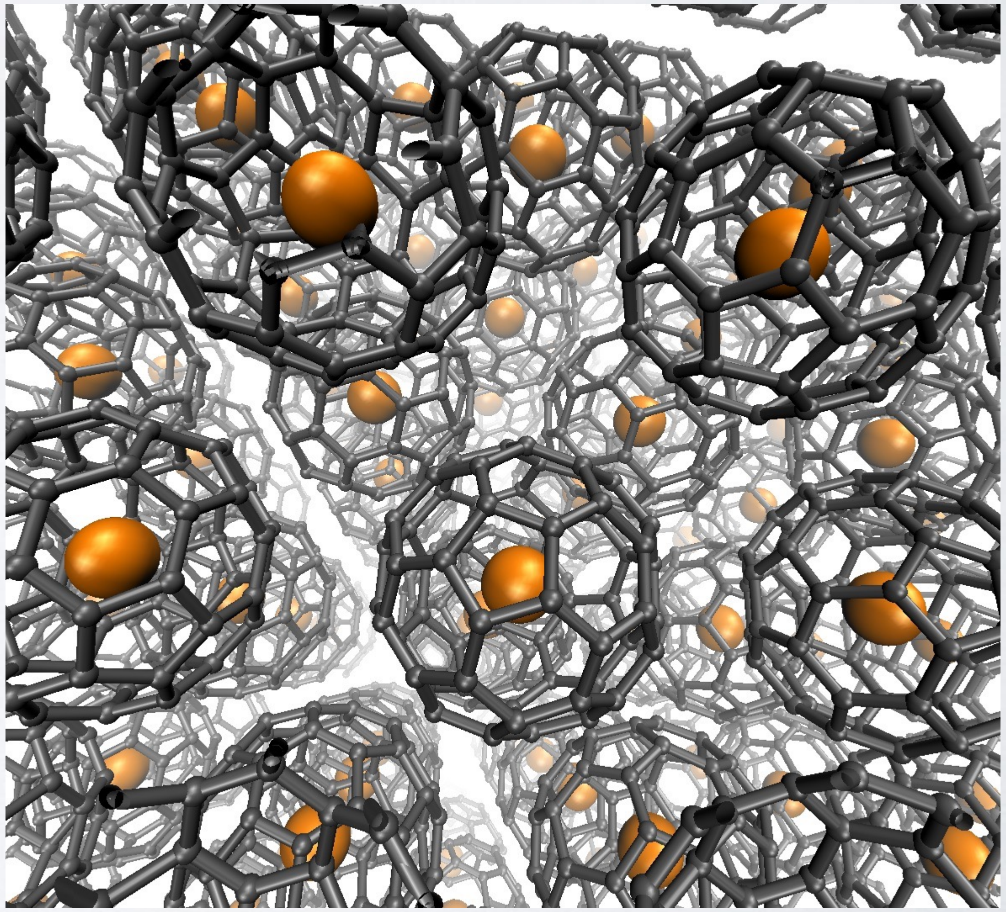
the nanotube potential looks like

[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

$E\_e=q(V_{TES}-V\_source)+E\_cal$

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): ΔE_{FWHM} = 0.05 eV @ 10 eV

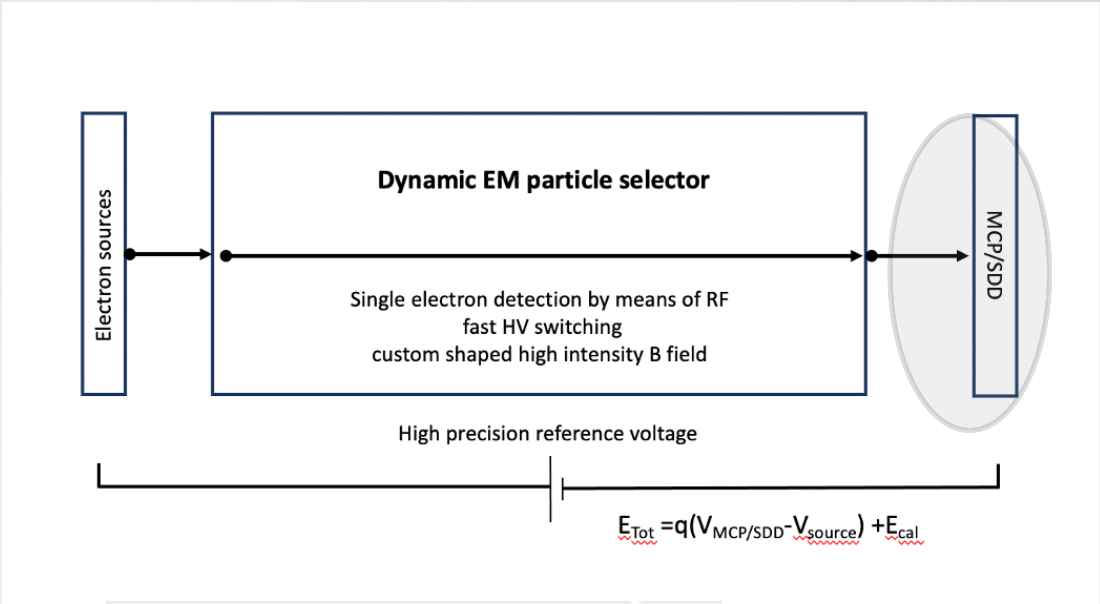
translates to $\Delta E \propto E^{\alpha}$ $(\alpha \leq 1/3)$

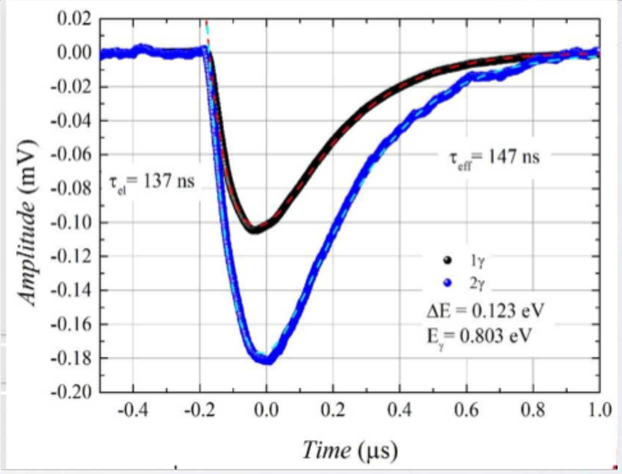
ΔE_{FWHM} = 0.022 eV @ 0.8 eV

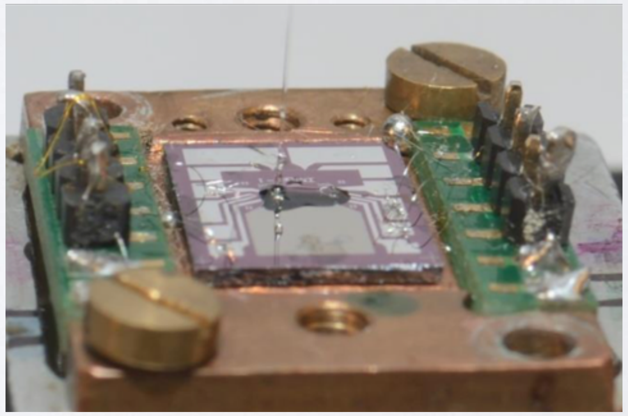
$$\Delta E_{FWHM} \approx 2.36 \sqrt{4 k_B T_c^2 \frac{C_e}{\propto} \sqrt{\frac{n}{2}}}$$

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

⇨ T_c= 46 mK @10x10 μm² (t=45 nm)





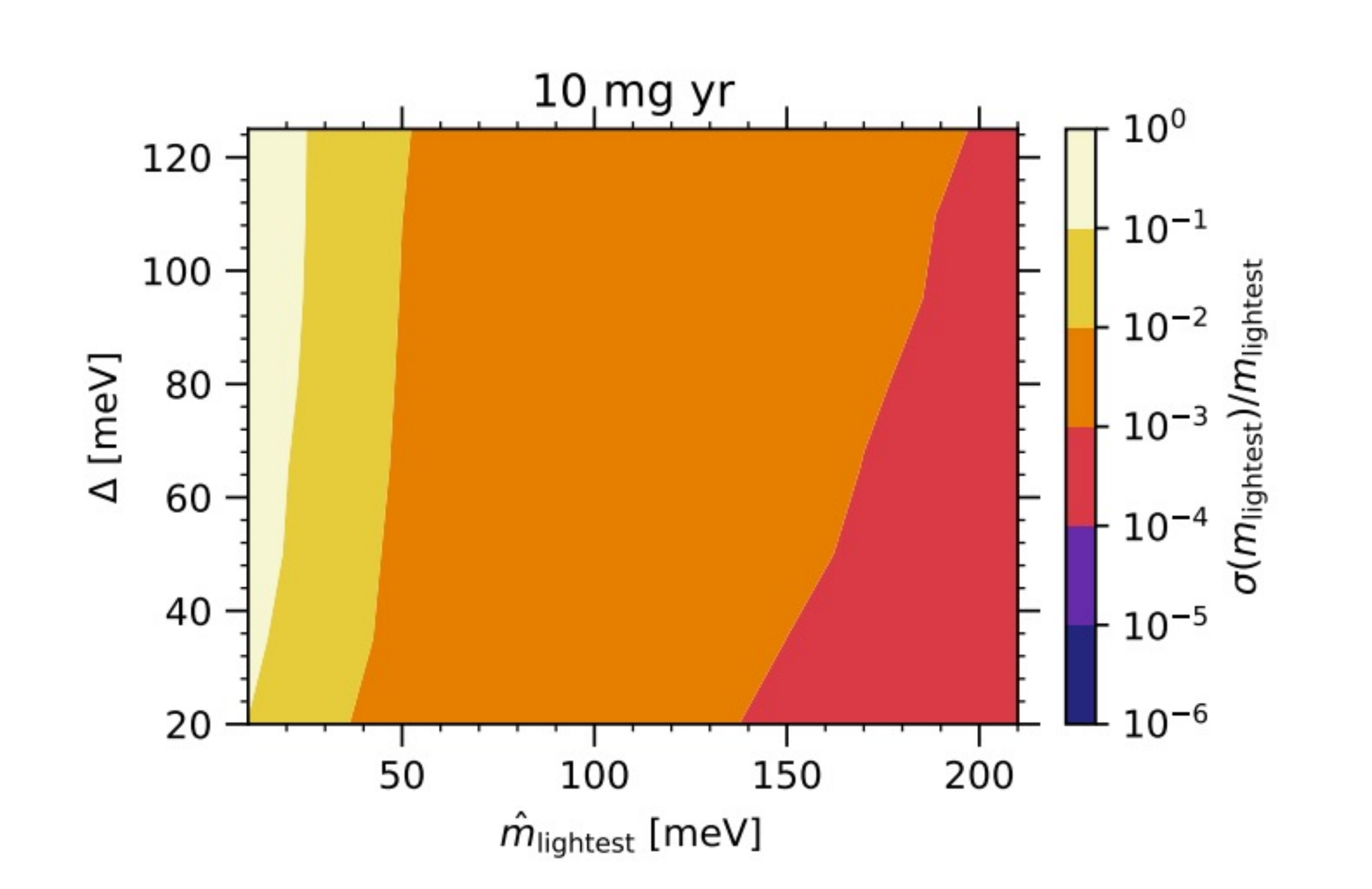


INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

A taste of the results that PTOLEMY can achieve

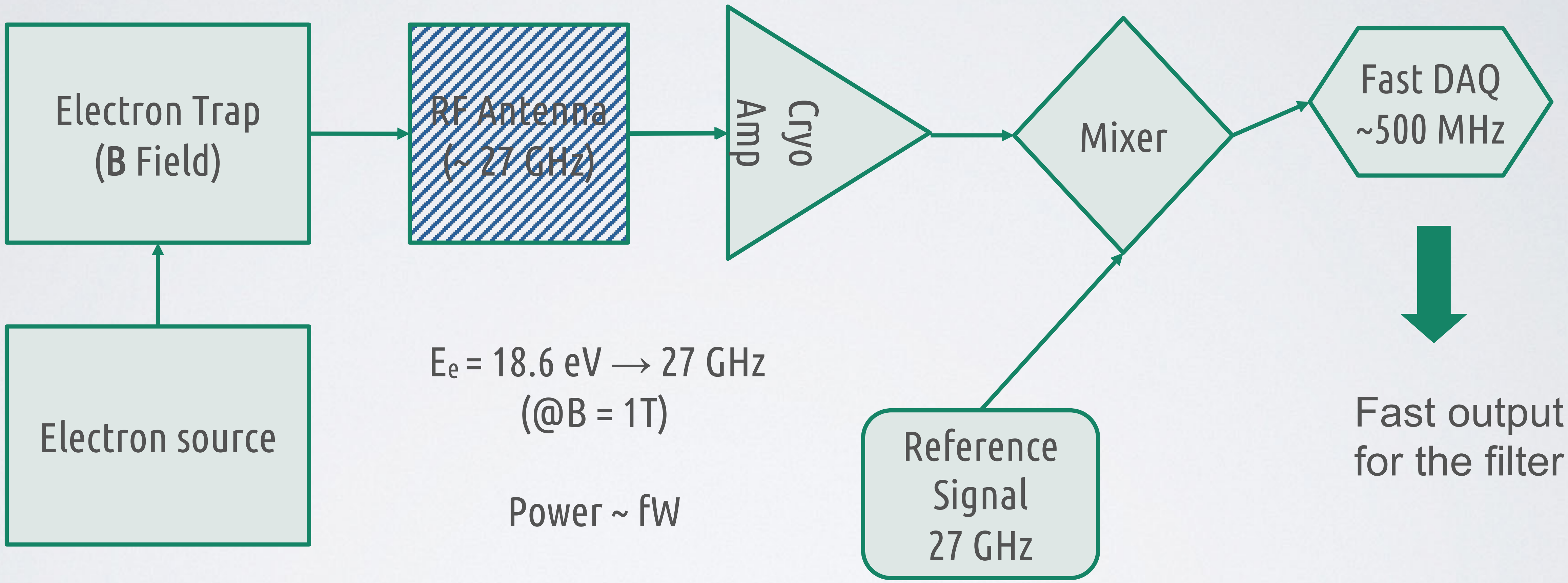
Even in absence of capture events spectral analysis will allow to achieve mass measurement with the percentage uncertainty reported below:

energy resolution versus lights neutrino mass for 10 mg x yr of exposures



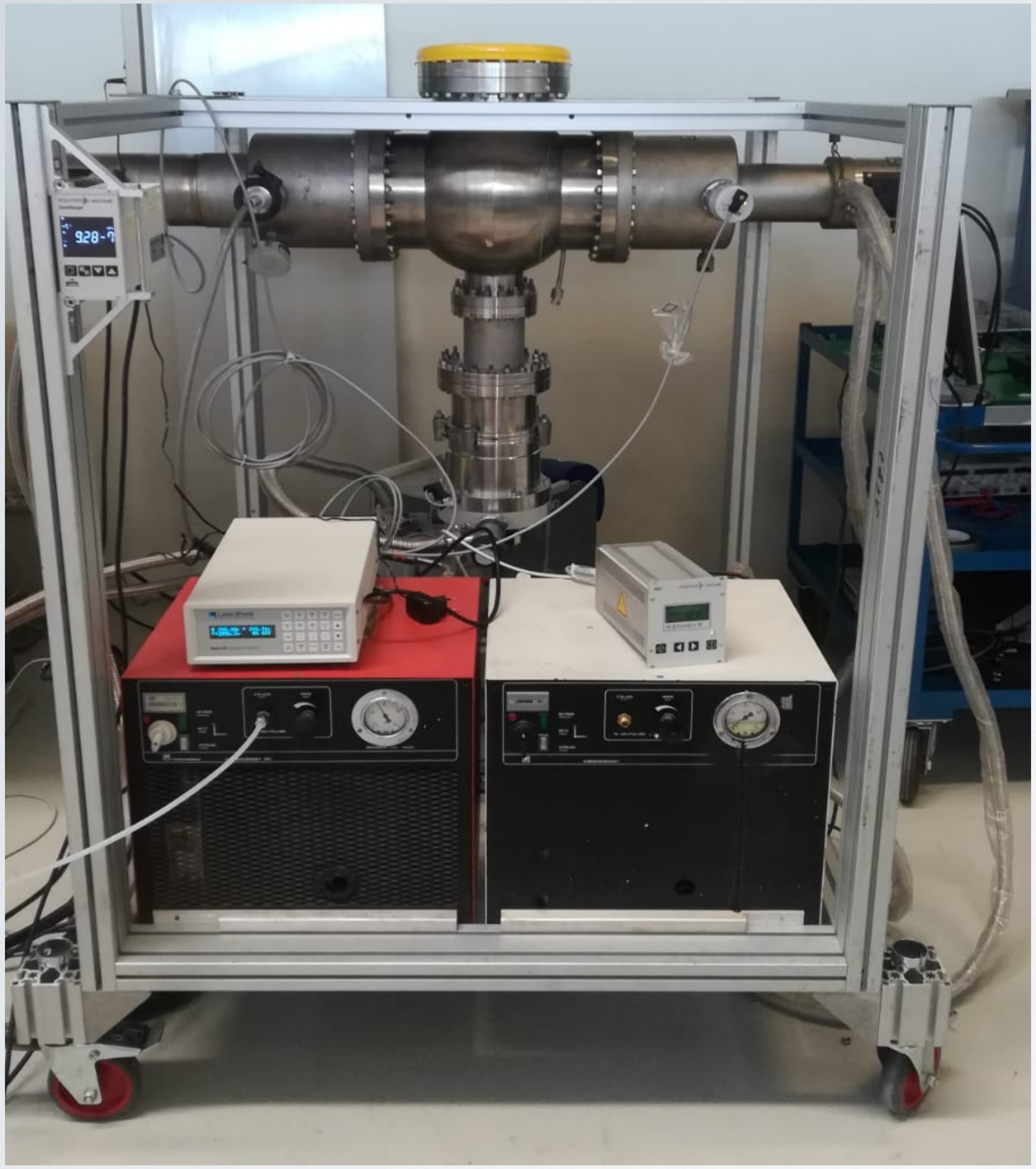
R&D at LNGS

RF ANTENNA R&D



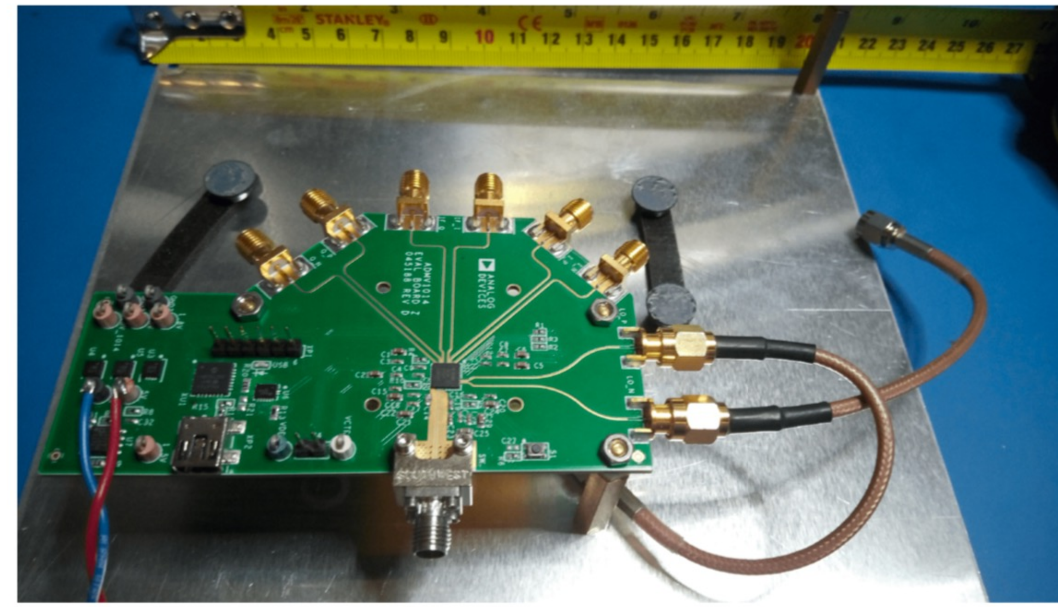
RF R&D AT LNGS

RF cryogenic system

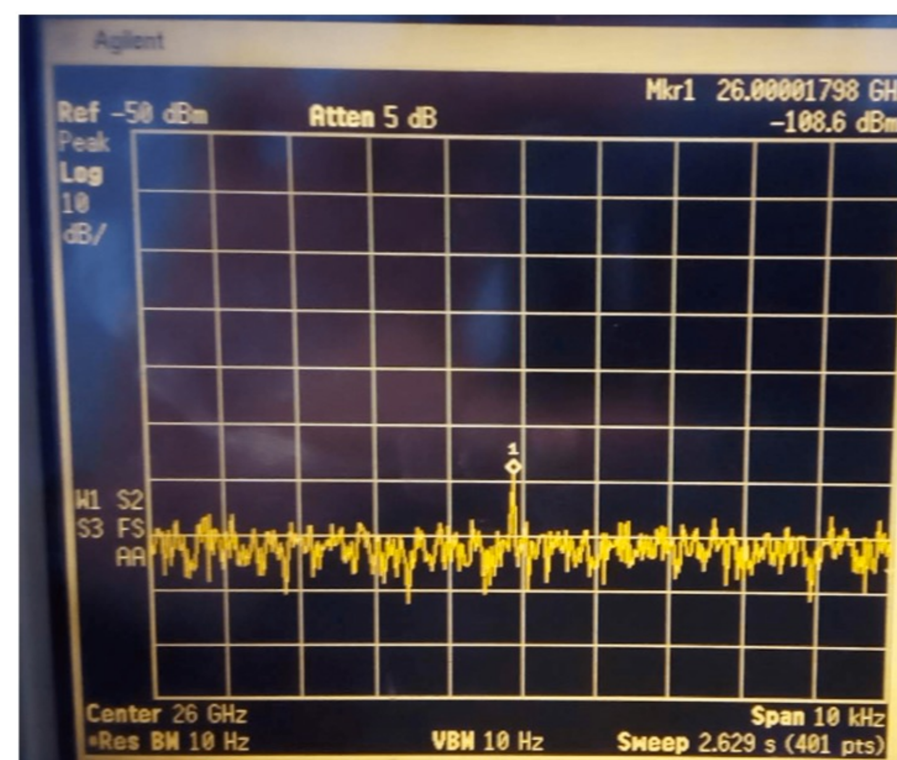


Frequency Down-conversion

- $f_{IF} = f_{RF} - f_{LO}$, ADMV1014, $G_{mixer}(f_{IF} = 1GHz) = 17.5dB$

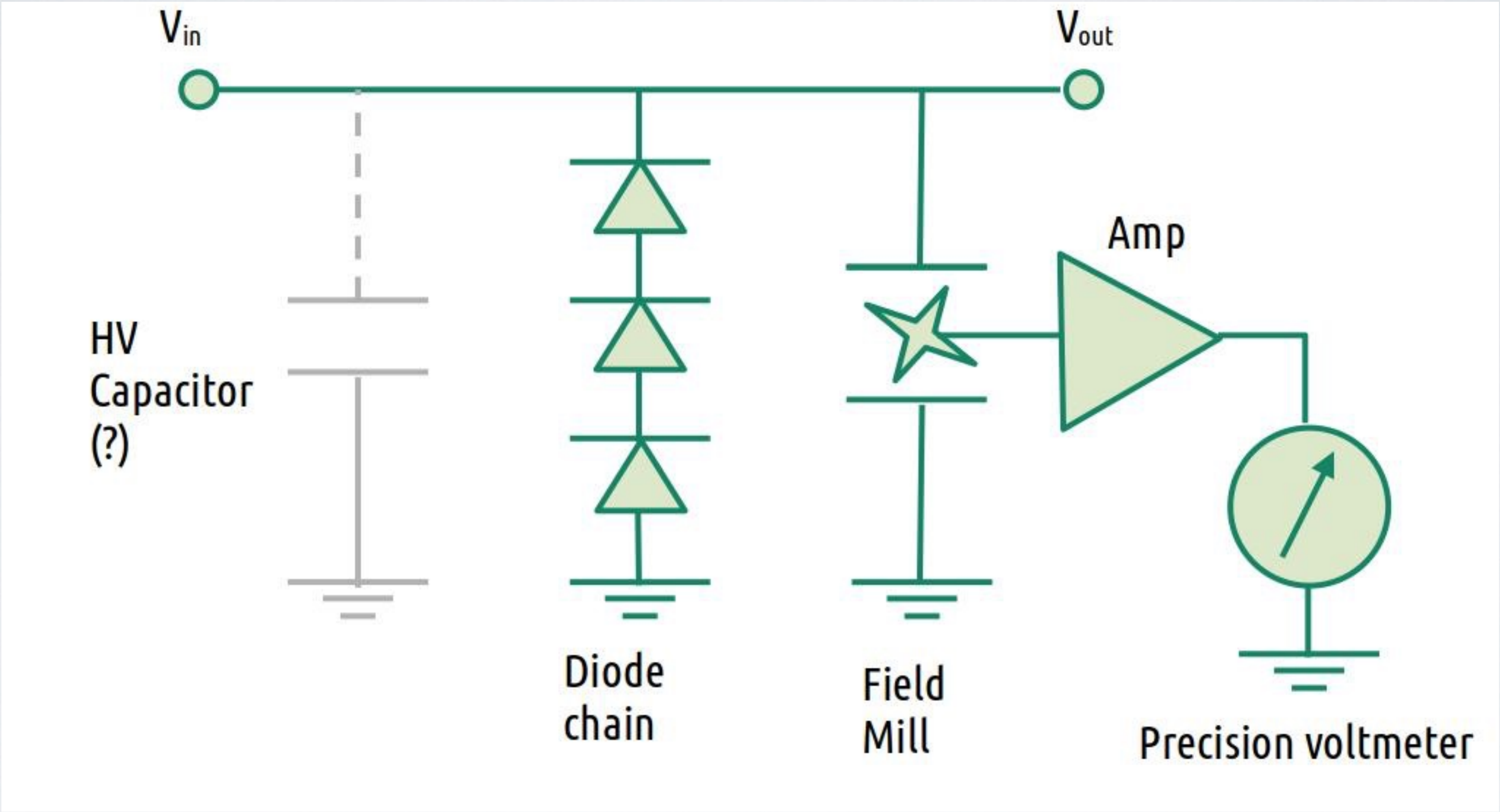


Results



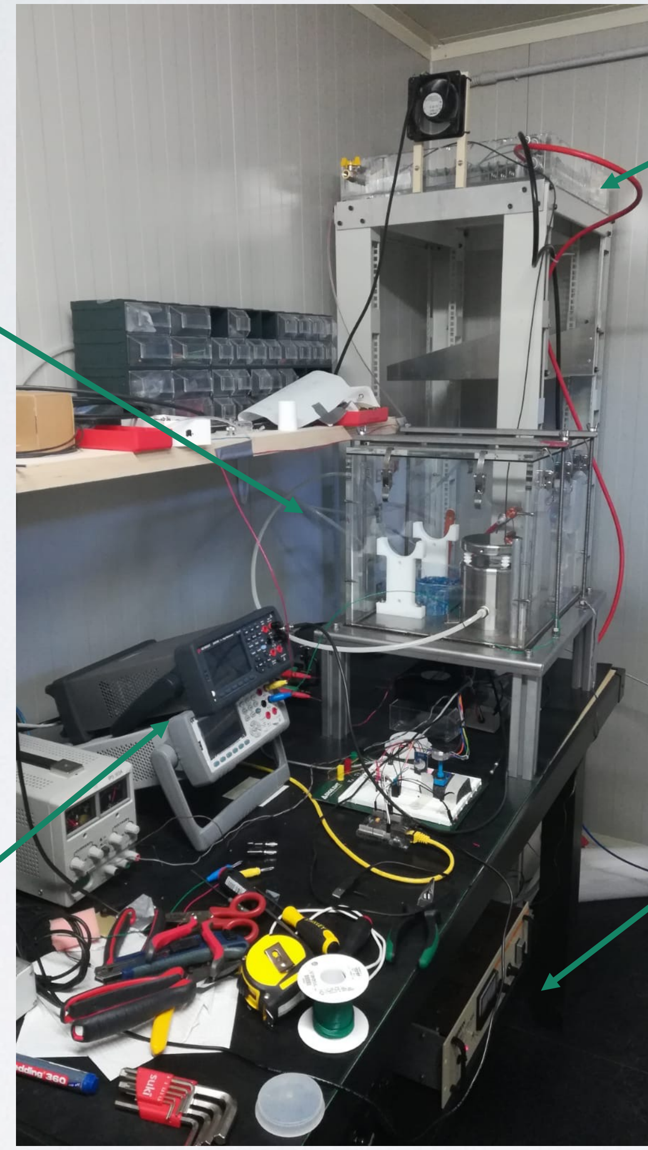
HV precision reference

goal: <10 mV over 20000 V

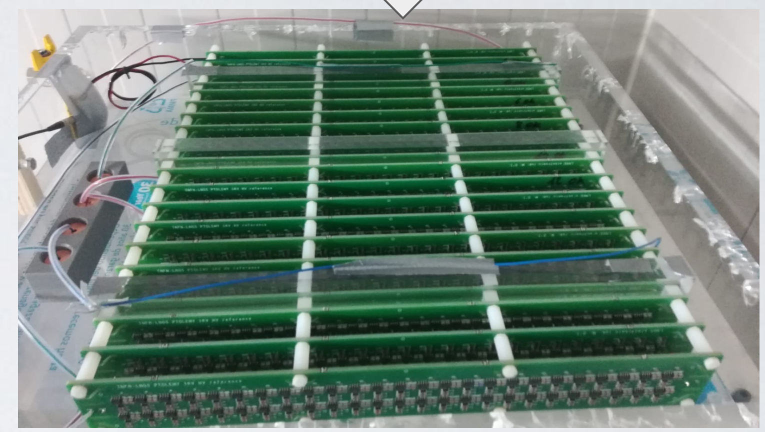


Experimental SETUP (@LNGS)

Field mill box

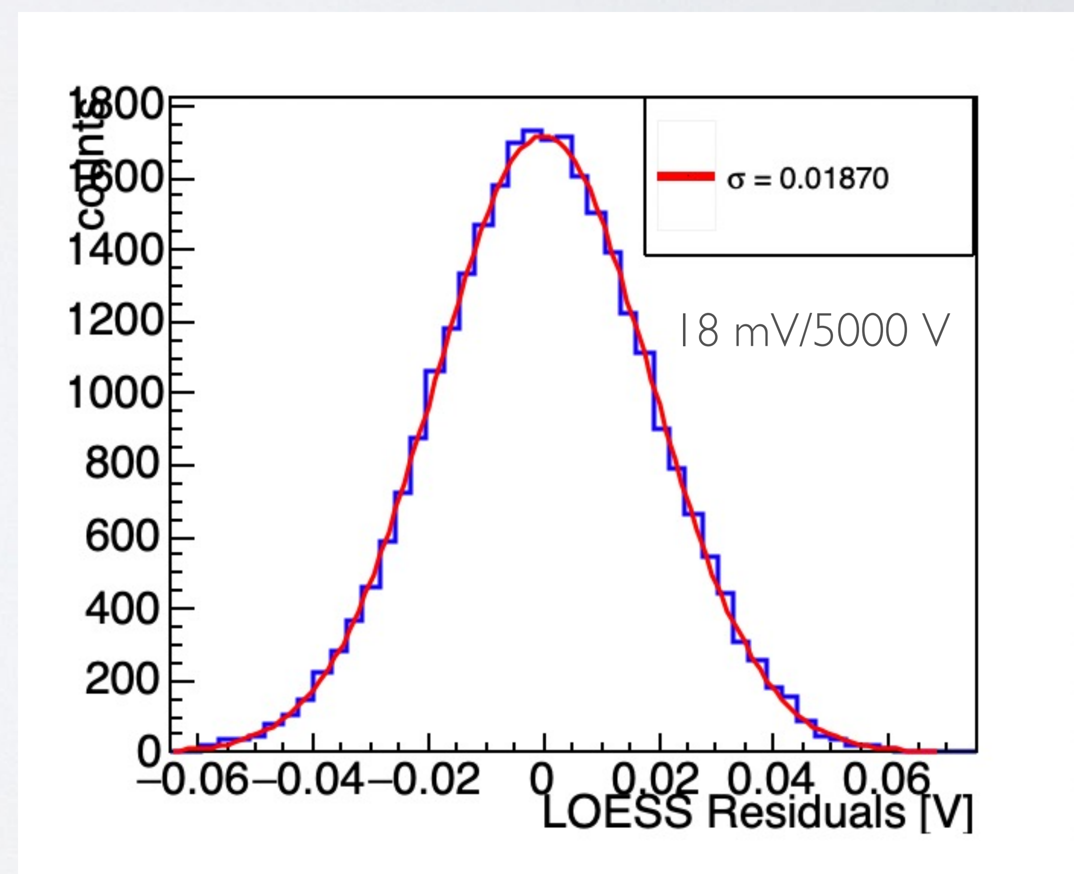


Diodes box



High precision voltmeter
Keysight®

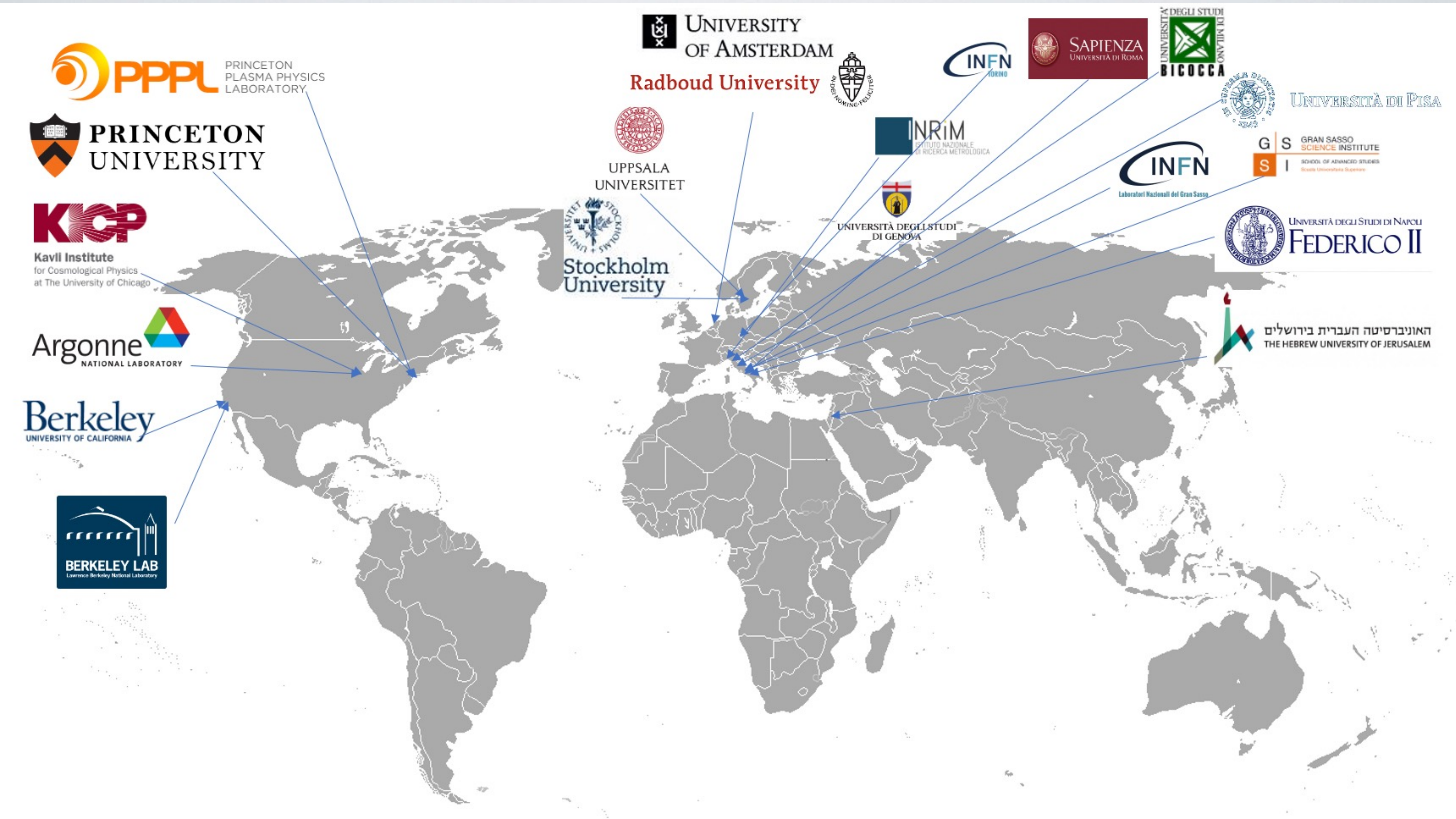
Power supply
Bertan®

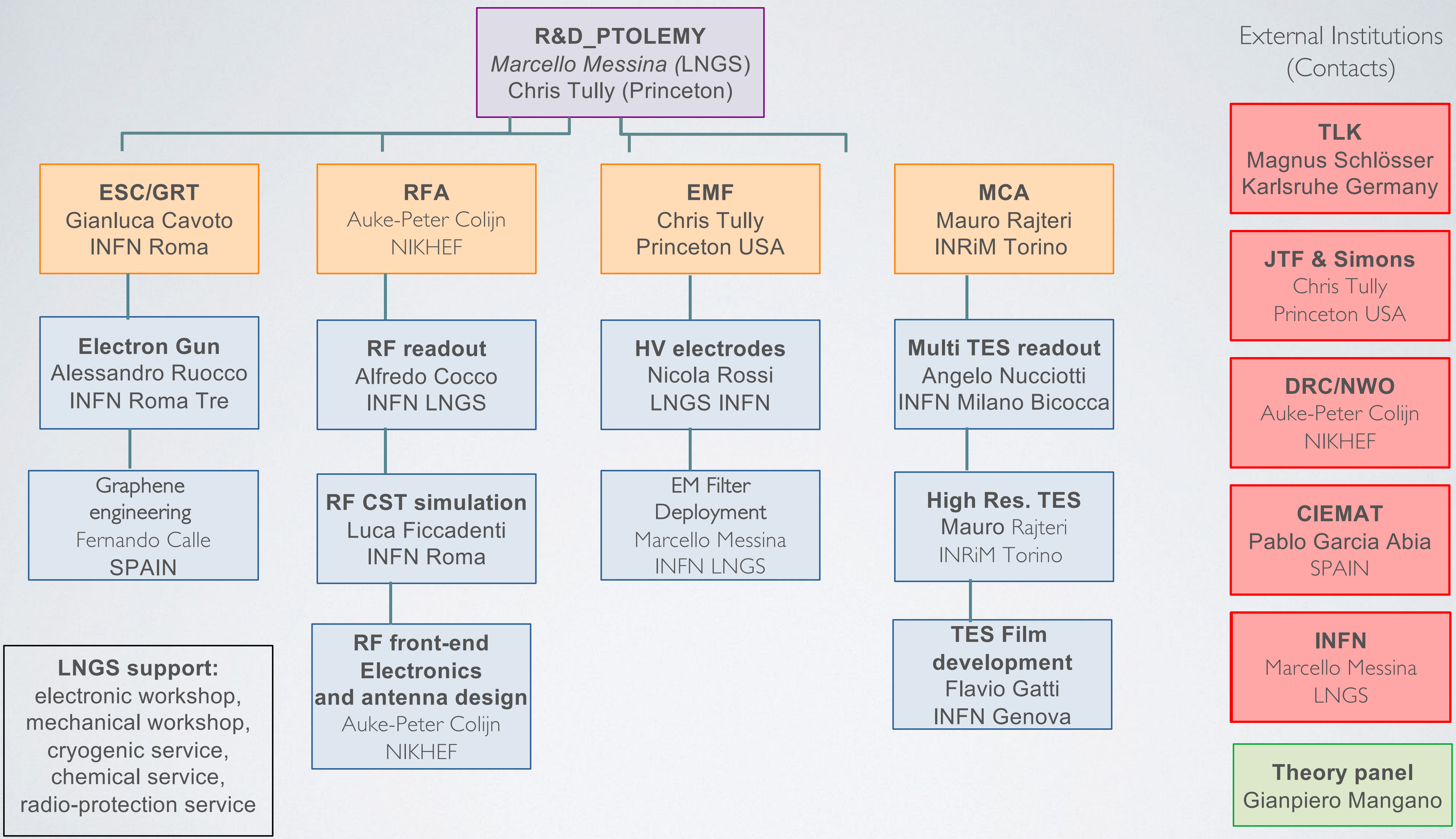


PTOLEMY SCHEDULE

- **CONCEPTUAL DESIGN REPORT,** 2023
- **PTOLEMY DEMONSTRATOR, 0.1 MG SOURCE** (NEUTRINO MASS), 2025
- **FULL SCALE EXPERIMENT (**> 2030)
  – GRAPHENE PACKAGING
  – MODULAR DETECTOR

PTOLEMY COLLABORATORS ALL AROUND THE WORLD




R&D_PTOLEMY
Marcello Messina (LNGS)
Chris Tully (Princeton)
ESC/GRT
Gianluca Cavoto
INFN Roma
RFA
Auke-Peter Colijn
NIKHEF
EMF
Chris Tully
Princeton USA
MCA
Mauro Rajteri
INRiM Torino
Electron Gun
Alessandro Ruocco
INFN Roma Tre
RF readout
Alfredo Cocco
INFN LNGS
HV electrodes
Nicola Rossi
LNGS INFN
Multi TES readout
Angelo Nucciotti
INFN Milano Bicocca
Graphene engineering
Fernando Calle
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RF CST simulation
Luca Ficcadenti
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EM Filter Deployment
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High Res. TES
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RF front-end Electronics and antenna design
Auke-Peter Colijn
NIKHEF
TES Film development
Flavio Gatti
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LNGS support:
electronic workshop,
mechanical workshop,
cryogenic service,
chemical service,
radio-protection service
External Institutions (Contacts)
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Karlsruhe Germany
JTF & Simons
Chris Tully
Princeton USA
DRC/NWO
Auke-Peter Colijn
NIKHEF
CIEMAT
Pablo Garcia Abia
SPAIN
INFN
Marcello Messina
LNGS
Theory panel
Gianpiero Mangano

FINANCIAL SUPPORT

Previous financial supports:

Princeton Univ., Simons Foundation (2016-): 3 M$, plus 2 M$ current grant

John Templeton Foundation 1 already given and 1 M$ current grant dedicated to the design study of the PTOLEMY filter.

Dutch Research Council (NL) (2021-): 1.3 ME

Research Grant of "One Second after the Big Bang"
The topic of the grant is "**RF antenna design and large scale readout chain implementation.**"
LNGS is a partner in this grant. One PhD position is awarded and one PostDoc, 60% based at LNGS with 100 kE budget, are foreseen.

Italian program of PNRR: 400 kE out of almost_2 M grant of a technological project dedicated to the 3D additive metal manufacturing development. This budget will be exploited for the construction of the demonstrator at LNGS.

R&D ongoing at LNGS presently supported by **CSNV with almost 50 kE per year for three years** (not included the researcher salary)

CONCLUSION

- PTOLEMY aims at eventually detect cosmic neutrino background on a long term time scale
- The detector prototype will be ready at LNGS by the 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 measurement
- 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.

Thanks for listening!