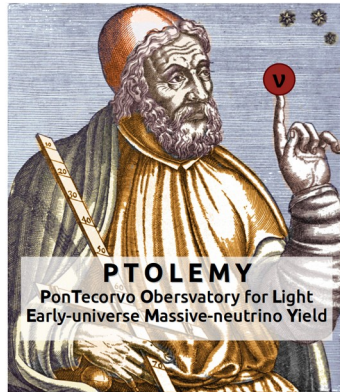


Detection of Cosmic Neutrino Background with the “PTOLEMY” experiment



**SEMINARIUM
ASTROFIZYCZNE**

WFAIS UJ oraz Komisji Astrofizyki PAU

Jagiellonian University, Dec 22th 2021



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Laboratori Nazionali del Gran Sasso
Istituto Nazionale di Fisica Nucleare (INFN)
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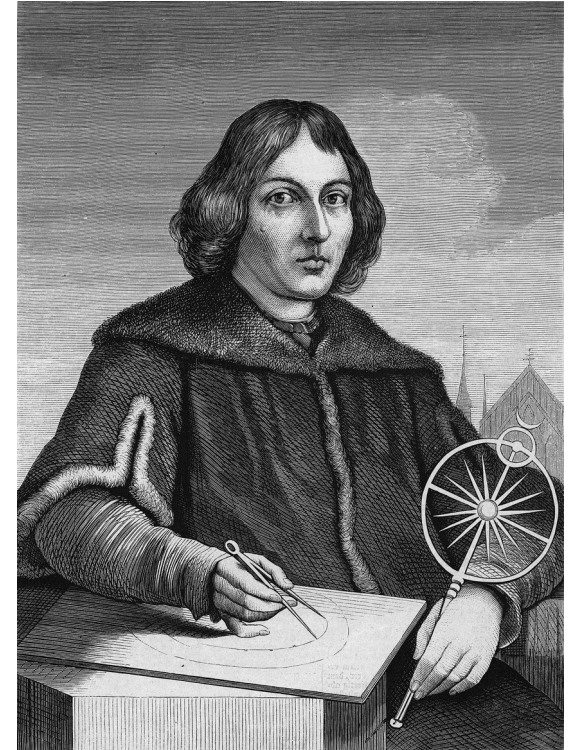
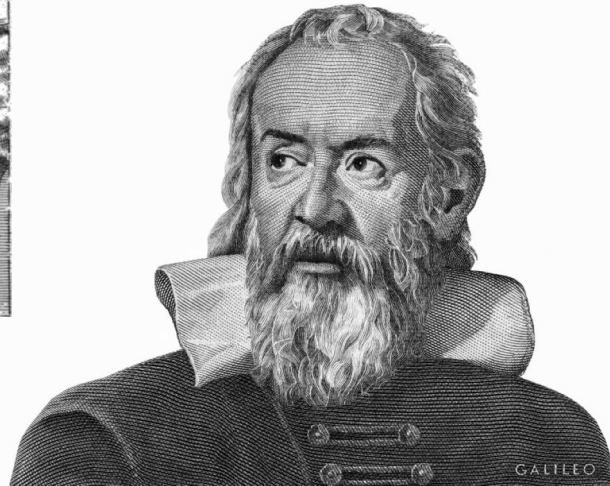
Dialogue Concerning the Two Chief World Systems



Claudius Ptolemaeus

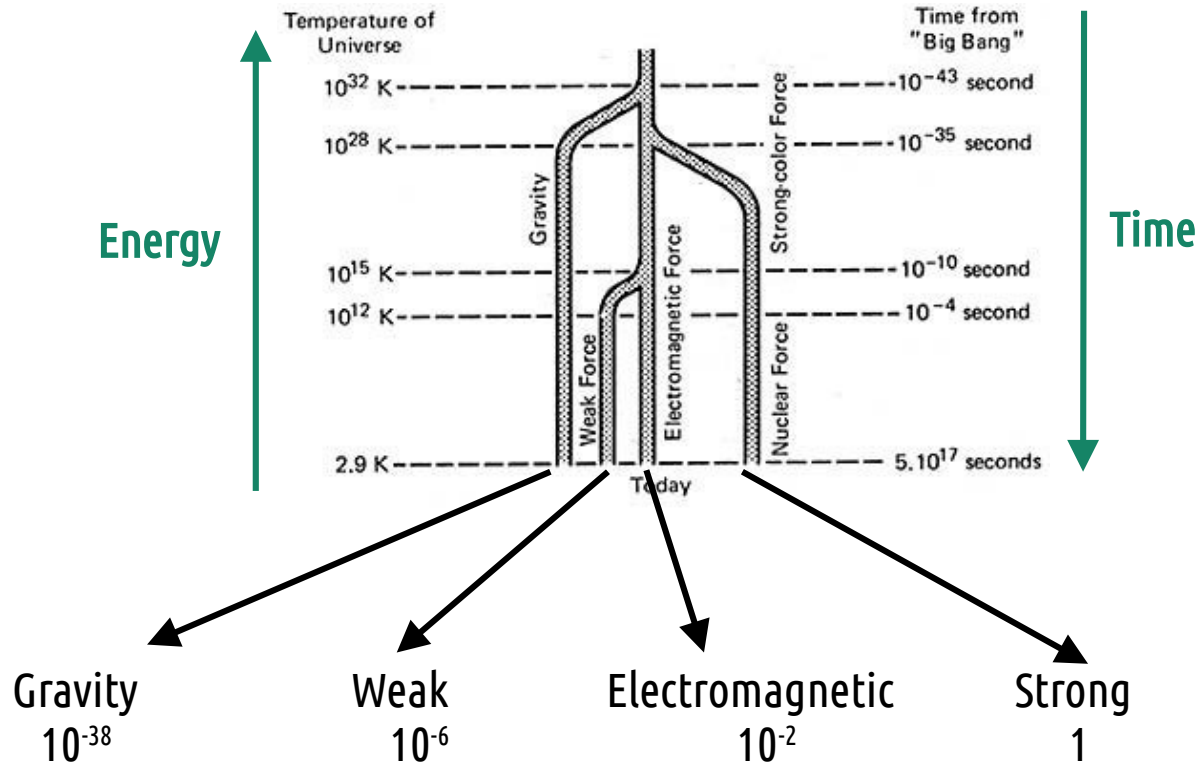
Sorry if I disturb you
at your house again!
This time is not about sun

Galileo Galilei



Nicolaus Copernicus

Four interactions from One (?)



Forces & Particles

Quarks	u up	c charm	t top	γ photon
	d down	s strange	b beauty	W^{\pm} W boson
Leptons	e electron	μ muon	τ tau	Z^0 Z boson
	ν_e neutrino electron	ν_{μ} neutrino muon	ν_{τ} neutrino tau	g gluon

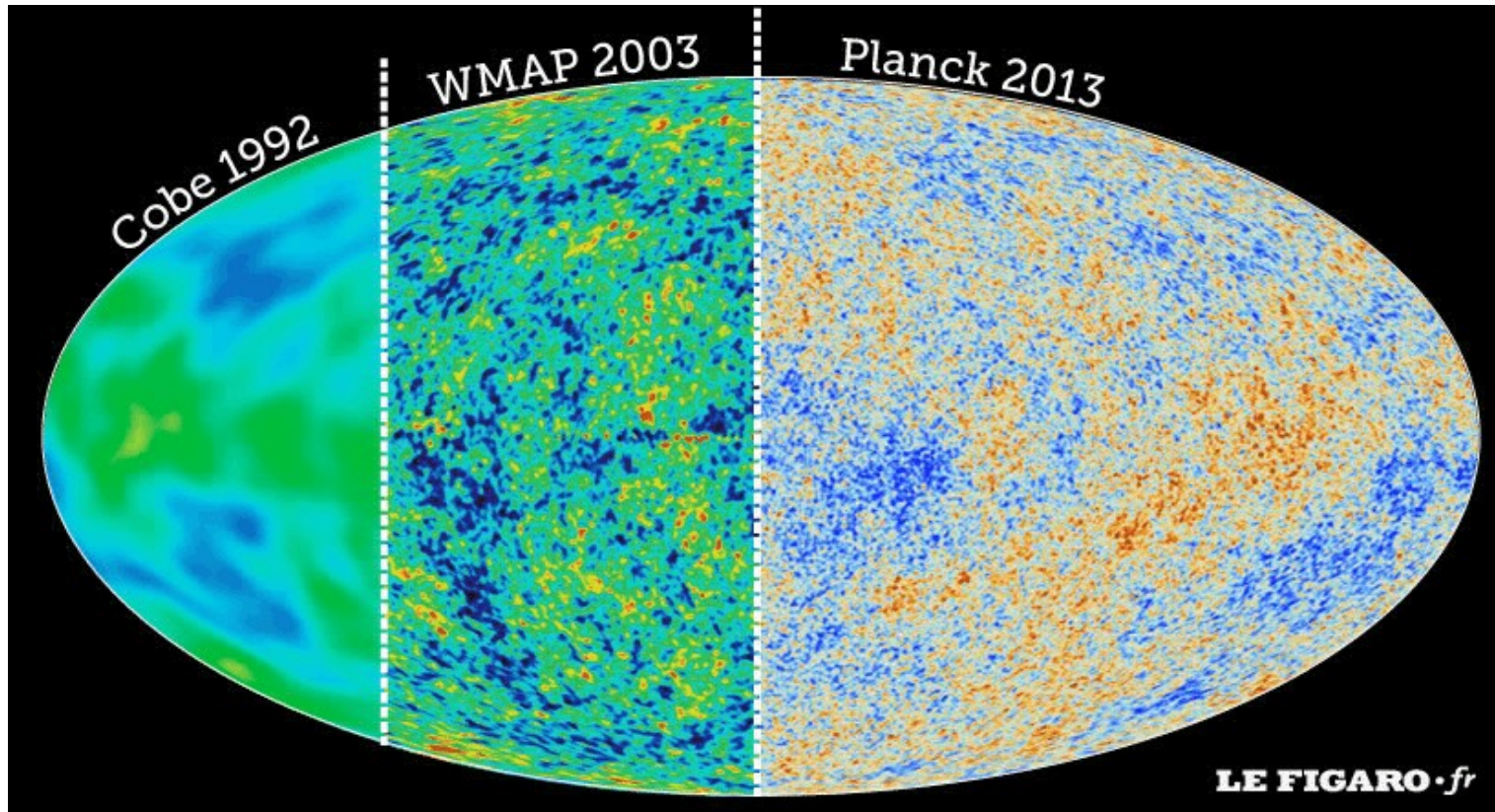
Main evidences in favor

- 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**: ^4He , ^2H , ^7Li (?)
- **Galaxies morphology** and stars populations in time
- **Primordial gas cloud** (without heavy elements), 2011

Important issues

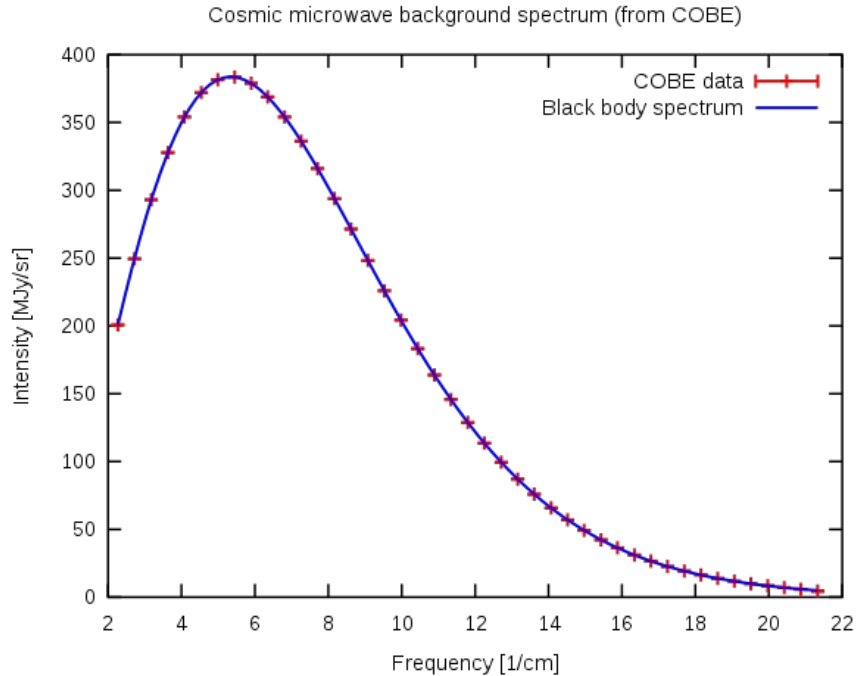
- **Baryon asymmetry**, $\eta = 10^{-10}$
- **Dark energy** (~70%) and **dark matter** (~25%) still unknown
- **Horizons** and **flatness** problem: cosmological constant and inflation

The gold mine of cosmologists

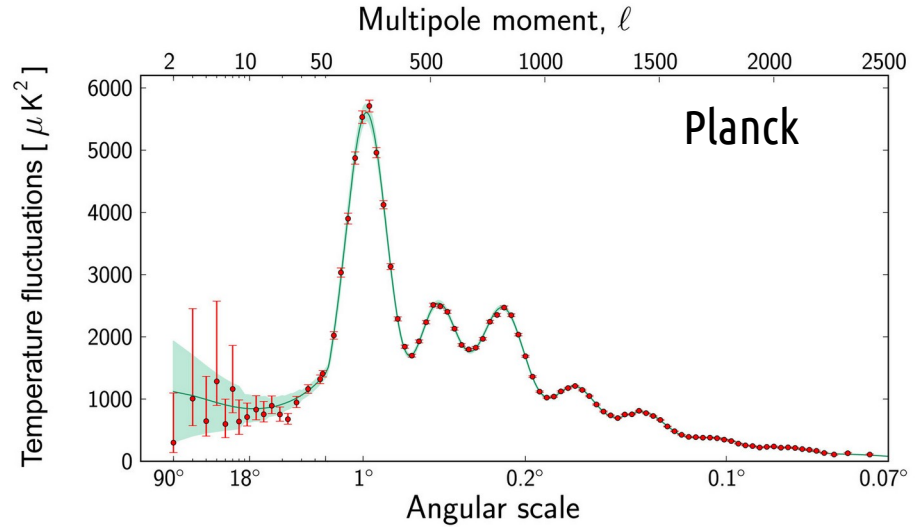


CMB: The oldest electromagnetic radiation in the universe

Cosmic Microwave Radiation

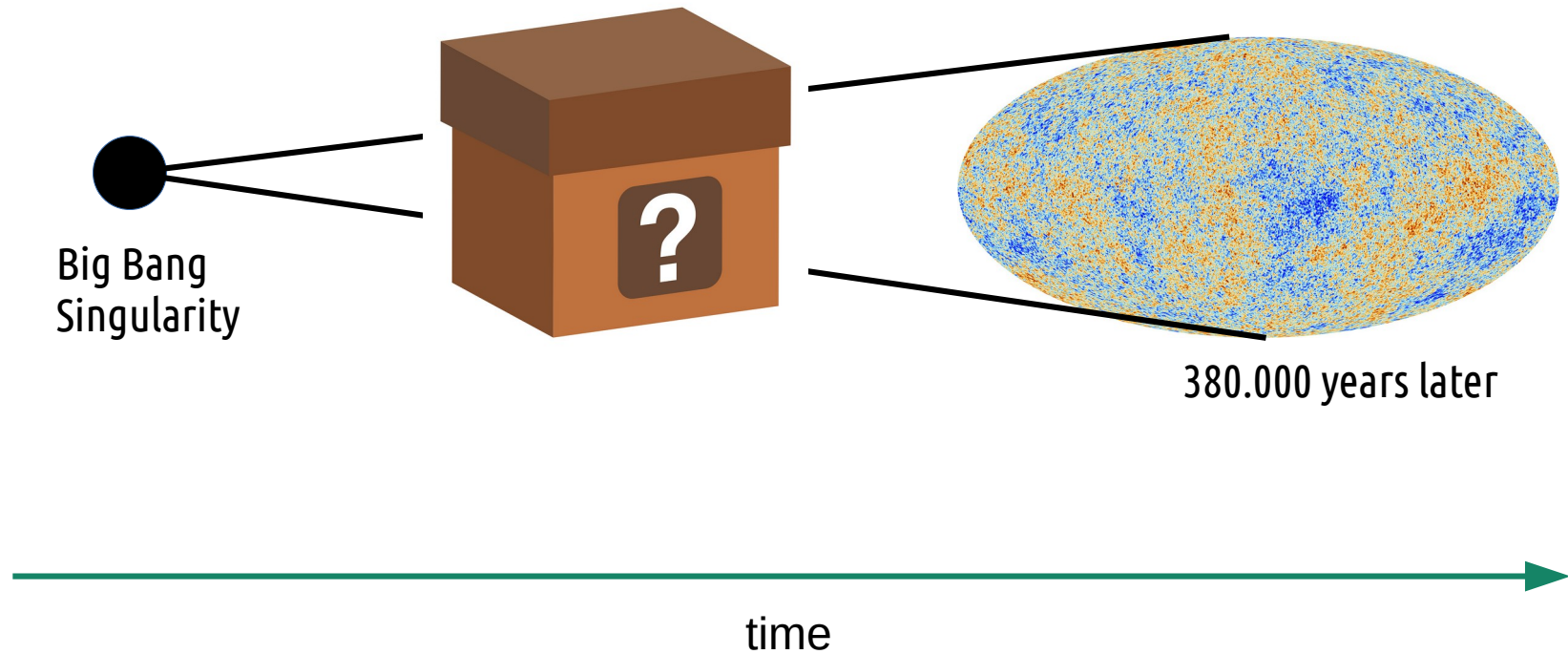


Black body radiation
 $T = 2.75 \text{ K}$



Anisotropies
 $\delta T/T \sim 10^{-5}$

Is there anything older than CMB?



A more precious mine: at the very early universe



Cosmic Neutrino Background, only 1s after the beginning

The oldest particle of the universe

Original Autogram of Pauli 1930
Abschrift/15.12.30 PM

Offener Brief an die Gruppe der Radioaktiven bei der
Gouvernements-Tagung in Wurzburg.

Abschrift
Physikalisches Institut
der Hohg. Technischen Hochschule
Zurich

Wurzburg, 14. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

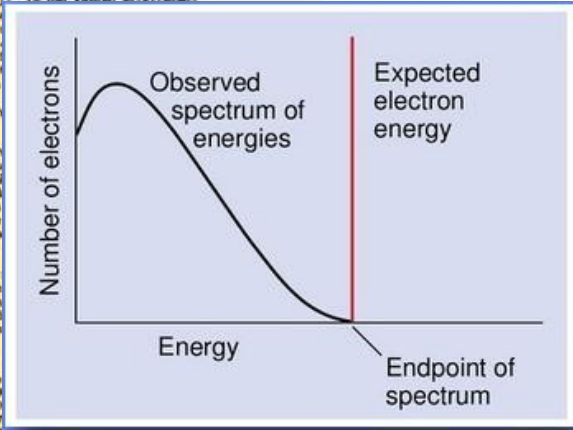
Wie der Uebersetzer dieser Zeilen, den ich halbvollst-
andhurgen bitte, Ihnen das aherem zusammenzufassen wird, bin ich
angelegentlich der "falschen" Statistik der β - und β - γ Kurve, sowie
des kontinuierlichen β -Spektrums auf einen verwechelteten Ausweg
verfallen um den "Wochenblatt" (1) der Statistik und den Energiezustand
zu retten. Moglich die Moglichkeit, es konnten elektrisch neutrale
Teilchen, die ich Neutronen nennen will,
welche den Spdn $1/2$ haben und das Atom
wird von Lichtgeschwindigkeit ausserhalb noch
sich mit Lichtgeschwindigkeit laufen
sinnlos von derselben Grossenordnung
jedemfalls nicht grosser als 0,01. Freilich
kontinuum-Spektrum ware dann verandlich
 β -Zerfall mit dem elektronen jeweils
sind, damit, dass die Summe der Energien
konstant ist.

Was handelt es sich weiter der
Neutronen wirken. Das wahrscheinlich
sich aus wellenmechanischen Grunden (in
dieser Zeilen) dieses zu sein, dass die
wenn ein Dipol von einem gewissen
verhaltend ware, dass die Ionisierungs-
nicht grosser sein kann, als die eines
at wohl nicht grosser sein als e .

Ich trenne sich verlloslich aber
zu publizieren und werde mich erst von
Radioaktive, mit der Frage, wie es
eines solchen Neutronen stunde, wenn die
losel grosserer Durchdringungsvorgange
genau Strahl.

Ich gebe zu, dass mein Ausweg
wenig wahrscheinlich erweisen wird,
als statieren, wohl schon Konig ge-
genhat und der Ernst der Situation
wird durch einen Ausspruch meines
Herrn Debye, beabsichtigt, der mir Moglichkeit im voraus gesagt hat
"0, durch soll was sie besten gar nicht denken, sowie an die neuen
Stosser." Darum soll was jeden Weg zur Rettung ernstlich diskardieren.
Also, liebe Radioaktive, ruhe, und richte. Leider kann ich nicht
personlich in Wurzburg erscheinen, da ich infolge eines in der Nacht
vom 6. zum 7. Dez. in Zurich stattfindenden Ballas hier unabhanglich
bin. Mit vielen Grussen an Sie, sowie an Herrn Reak, hier
unterzeichnete Diener

gen. W. Pauli



Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to
him who knows how to wait.

Pauli

-RADIOGRAMME- RADIO-SPESER S.A.
116 W. CHICAGO ILL. 56 14 13111
P.C. 00153

BRITISCHGRAMM
74 15.11.30 -1 10

Per Post
PROFESSOR W. PAULI
ZURICH UNIVERSITY ZURICH ①
NACHLASS
PROF. W. PAULI

WE ARE HAPPY
NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY
OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX
TIMES TEN TO NINETY FORTY FOUR SQUARE CENTIMETERS
FREDERICK REINES AND CLYDE COWAN
BOX 1663 LOS ALAMOS NEW MEXICO



Wolfgang Pauli, 1930

Neutrinos

Neutrinos and Standard Model

three generations of matter (fermions)			interactions / force carriers (bosons)		
	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	u up	c charm	t top	g gluon	H higgs
	d down	s strange	b bottom	γ photon	
	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

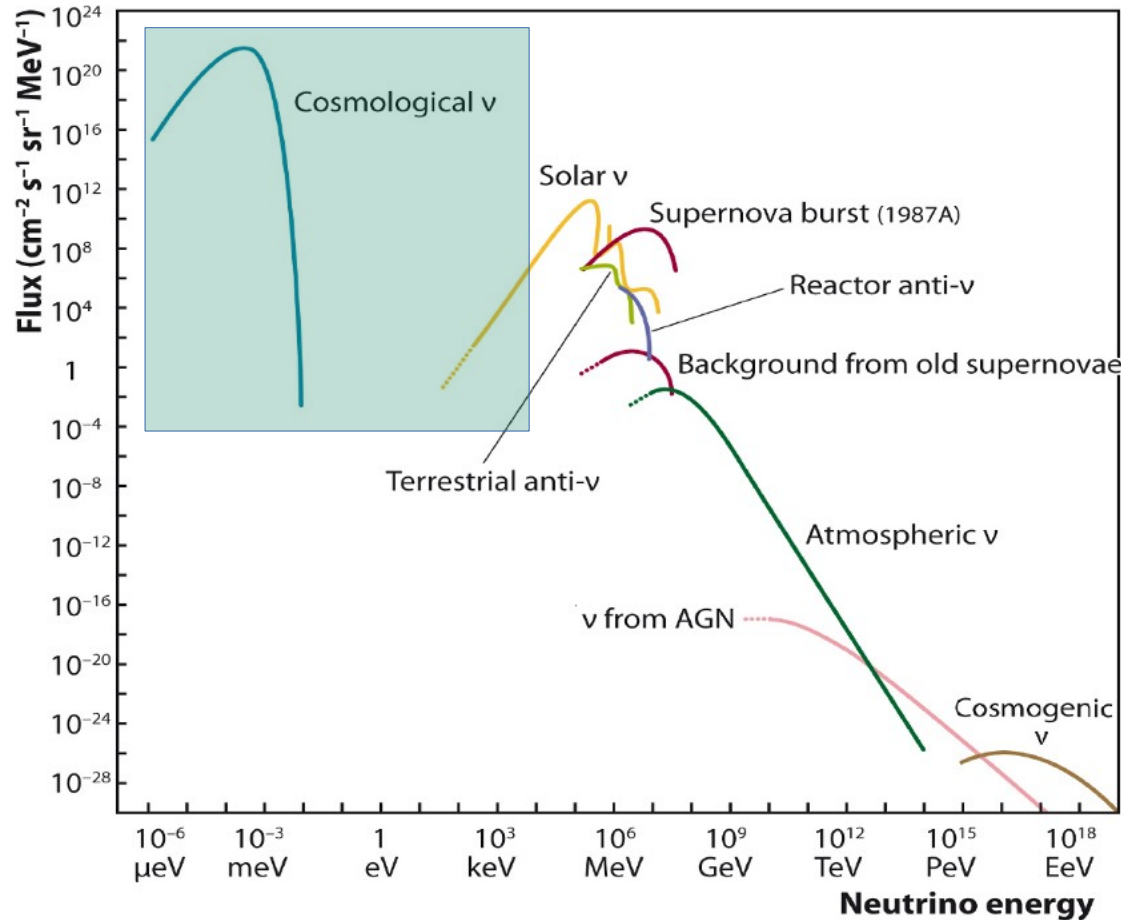
QUARKS (rows 1-3)
 LEPTONS (rows 4-5)
 GAUGE BOSONS VECTOR BOSONS (rows 4-5)
 SCALAR BOSONS (row 6)

- low interaction probability $\sigma \sim 10^{-44} \text{ cm}^2$

- three types
- light but not massless
- Oscillations

$$|\nu_\alpha\rangle = \sum_{i=1}^n U_{\alpha i}^* |\nu_i\rangle$$

Neutrino Sources



Cosmic neutrinos represent the **largest source** of available neutrinos

The only source **not yet detected**
Since 1956 (Reines & Cowan)

After ~90 years of Neutrino Physics

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric}} \cdot \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor}} \cdot \underbrace{\begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}}$$

$$P(\alpha \rightarrow \beta) \sim \sin^2(2\vartheta) \times \sin^2(\Delta m_{\alpha\beta}^2 L/(4E))$$

Experiment	Dominant	Important
Solar Experiments	θ_{12}	$\Delta m_{21}^2, \theta_{13}$
Reactor LBL (KamLAND)	Δm_{21}^2	θ_{12}, θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	$\theta_{13}, \Delta m_{31,32}^2 $	
Atmospheric Experiments (SK, IC-DC)		$\theta_{23}, \Delta m_{31,32}^2 , \theta_{13}, \delta_{\text{CP}}$
Accel LBL $\nu_\mu, \bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NO ν A)	$ \Delta m_{31,32}^2 , \theta_{23}$	
Accel LBL $\nu_e, \bar{\nu}_e$ App (MINOS, T2K, NO ν A)	δ_{CP}	θ_{13}, θ_{23}

	Ref. [188] w/o SK-ATM		Ref. [188] w SK-ATM		Ref. [189] w SK-ATM		Ref. [190] w SK-ATM	
NO	Best Fit Ordering		Best Fit Ordering		Best Fit Ordering		Best Fit Ordering	
Param	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2 \theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	2.75 → 3.50	$3.10^{+0.13}_{-0.12}$	2.75 → 3.50	$3.04^{+0.14}_{-0.13}$	2.65 → 3.46	$3.20^{+0.20}_{-0.16}$	2.73 → 3.79
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	31.61 → 36.27	$33.82^{+0.78}_{-0.76}$	31.61 → 36.27	$33.46^{+0.87}_{-0.88}$	30.98 → 36.03	$34.5^{+1.2}_{-1.0}$	31.5 → 38.0
$\frac{\sin^2 \theta_{23}}{10^{-1}}$	$5.58^{+0.20}_{-0.33}$	4.27 → 6.09	$5.63^{+0.18}_{-0.24}$	4.33 → 6.09	$5.51^{+0.19}_{-0.80}$	4.30 → 6.02	$5.47^{+0.20}_{-0.30}$	4.45 → 5.99
$\theta_{23}/^\circ$	$48.3^{+1.2}_{-1.9}$	40.8 → 51.3	$48.6^{+1.0}_{-0.9}$	41.1 → 51.3	$47.9^{+1.1}_{-0.8}$	41.1 → 50.9	$47.7^{+1.2}_{-1.7}$	41.8 → 50.7
$\frac{\sin^2 \theta_{13}}{10^{-2}}$	$2.241^{+0.066}_{-0.065}$	2.046 → 2.440	$2.238^{+0.065}_{-0.065}$	2.044 → 2.440	$2.41^{+0.06}_{-0.06}$	2.040 → 2.440	$2.160^{+0.083}_{-0.069}$	1.96 → 2.41
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	8.22 → 8.99	$8.60^{+0.13}_{-0.13}$	8.22 → 8.98	$8.41^{+0.18}_{-0.14}$	7.9 → 8.9	$8.45^{+0.16}_{-0.14}$	8.0 → 8.9
$\delta_{CP}/^\circ$	222^{+38}_{-28}	141 → 370	221^{+39}_{-28}	144 → 357	238^{+41}_{-33}	149 → 358	218^{+38}_{-27}	157 → 349
$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.39^{+0.21}_{-0.20}$	6.79 → 8.01	$7.39^{+0.21}_{-0.20}$	6.79 → 8.01	$7.34^{+0.17}_{-0.14}$	6.92 → 7.91	$7.55^{+0.20}_{-0.16}$	7.05 → 8.24
$\frac{\Delta m_{32}^2}{10^{-3} \text{ eV}^2}$	$2.449^{+0.032}_{-0.030}$	2.358 → 2.544	$2.454^{+0.029}_{-0.031}$	2.358 → 2.544	$2.419^{+0.035}_{-0.032}$	2.319 → 2.521	2.424 ± 0.03	2.334 → 2.524
IO	$\Delta\chi^2 = 6.2$		$\Delta\chi^2 = 10.4$		$\Delta\chi^2 = 9.5$		$\Delta\chi^2 = 11.7$	
$\frac{\sin^2 \theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	2.75 → 3.50	$3.10^{+0.13}_{-0.12}$	2.75 → 3.50	$3.03^{+0.14}_{-0.13}$	2.64 → 3.46	$3.20^{+0.20}_{-0.16}$	2.73 → 3.79
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	31.61 → 36.27	$33.82^{+0.78}_{-0.75}$	31.62 → 36.17	$33.40^{+0.87}_{-0.81}$	30.92 → 36.03	$34.5^{+1.2}_{-1.0}$	31.5 → 38.0
$\frac{\sin^2 \theta_{23}}{10^{-1}}$	$5.63^{+0.19}_{-0.26}$	4.30 → 6.12	$5.65^{+0.17}_{-0.22}$	4.36 → 6.10	$5.57^{+0.17}_{-0.24}$	4.44 → 6.03	$5.51^{+0.18}_{-0.30}$	4.53 → 5.98
$\theta_{23}/^\circ$	$48.6^{+1.1}_{-1.5}$	41.0 → 51.5	$48.8^{+1.0}_{-1.2}$	41.4 → 51.5	$48.2^{+1.0}_{-1.4}$	41.8 → 50.9	$47.9^{+1.0}_{-0.8}$	42.3 → 50.7
$\frac{\sin^2 \theta_{13}}{10^{-2}}$	$2.261^{+0.067}_{-0.064}$	2.066 → 2.461	$2.259^{+0.065}_{-0.065}$	2.064 → 2.457	$2.18^{+0.08}_{-0.07}$	1.95 → 2.44	$2.220^{+0.074}_{-0.069}$	1.96 → 2.44
$\theta_{13}/^\circ$	$8.65^{+0.13}_{-0.12}$	8.26 → 9.02	$8.64^{+0.12}_{-0.13}$	8.26 → 9.02	$8.49^{+0.15}_{-0.14}$	8.0 → 9.0	$8.53^{+0.14}_{-0.14}$	8.1 → 9.0
$\delta_{CP}/^\circ$	285^{+24}_{-26}	205 → 354	282^{+23}_{-25}	205 → 348	247^{+26}_{-27}	193 → 340	281^{+26}_{-27}	202 → 349
$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.39^{+0.21}_{-0.20}$	6.79 → 8.01	$7.39^{+0.21}_{-0.20}$	6.79 → 8.01	$7.34^{+0.17}_{-0.14}$	6.92 → 7.91	$7.55^{+0.20}_{-0.16}$	7.05 → 8.24
$\frac{\Delta m_{32}^2}{10^{-3} \text{ eV}^2}$	$-2.509^{+0.032}_{-0.032}$	-2.603 → -2.416	$-2.510^{+0.030}_{-0.031}$	-2.601 → -2.419	$-2.478^{+0.035}_{-0.033}$	-2.577 → -2.375	$-2.50 \pm^{+0.04}_{-0.03}$	-2.59 → -2.39

The nature was so kind

$\Delta m_{21}^2 \sim 10^5 \text{ eV}^2$

$\Delta m_{32}^2 \sim 10^3 \text{ eV}^2$

$\theta_{12} \sim \theta_{23}$ large

θ_{13} small

Details:

- CP phase
- Mass ordering (m_1, m_2, m_3)
- Majorana/Dirac
- Sterile neutrinos (???)
- nearly three types
- NSI

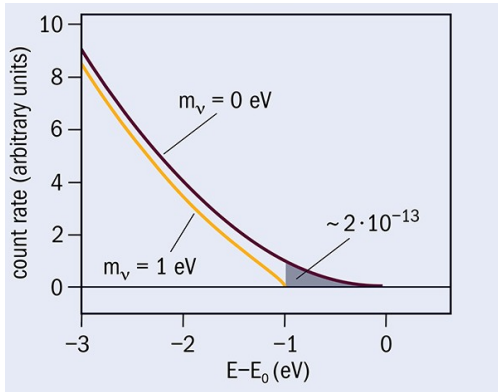
Neutrino mass

1. KATRIN experiment

From beta decay

$$m_{\nu_e} < 1.1 \text{ eV (95\% CL)}$$

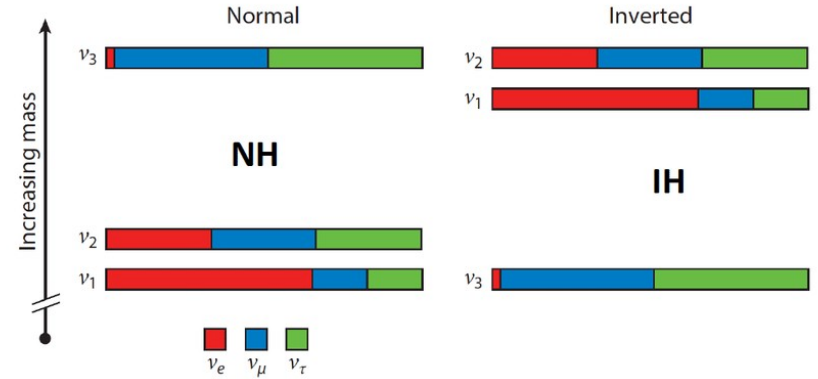
[M. Aker et al., 2019]



Tritium beta decay



ordering



2. Cosmology

$$S = \sum m_i$$

$$m_\nu < 50 \text{ meV}$$



CNB or CvB or Relic Neutrinos

- From ~ 1 s old universe

- $T = 1.95$ K

- $E \sim 10^{-6} \div 10^{-4}$ eV

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

- Strong **indirect evidence** from Cosmology:
BBN (D, ^4He), CMB $\rightarrow 3\nu$ and T_ν , ...
- But... **no direct evidence yet**

Direct CNB search

Not possible: $\bar{\nu} + p \rightarrow n + e^+$

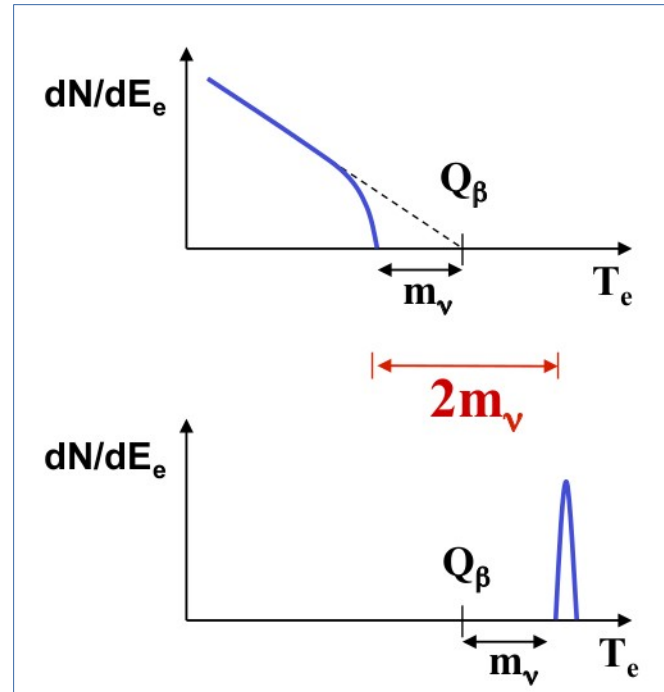
Then:

- **Coherent scattering** of solid object, $a = 10^{-23} \text{ m/s}^2$
- Scattering on **accelerator** beam, ULHC
- **Cosmic ray** scattering
- **Neutrino capture on beta unstable nuclei**

Neutrino Capture

- **Beta unstable** nucleus A
- **Threshold-less** reaction
 $\nu_e + A \rightarrow B + e^-$
- **Monochromatic** peak at $Q+m_\nu$
- Neutrino **mass as by product** from the CNB detection!

[A. Cocco et al, 2007]

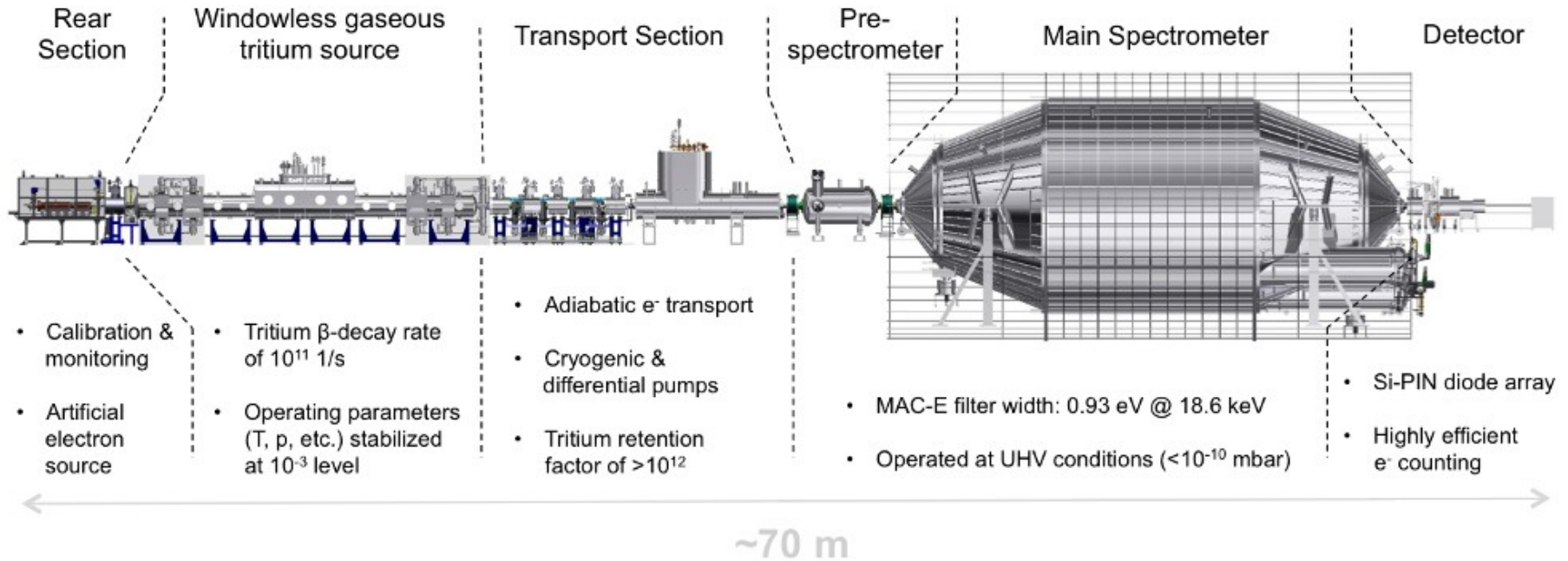


Tritium: the best candidate

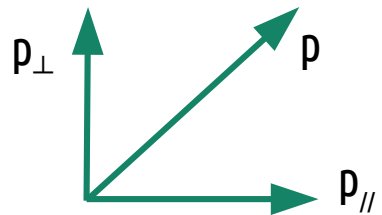
- **Low Q = 18.57 keV**
- **Reasonable halflife $T_{1/2}=12.32$ y (high rate but not that fast)**
- **Simple nuclear structure, no nuclear structure corrections**
- **Relatively high cross section (constant)**

$$\sigma \sim 10^{-44} \text{ cm}^2$$

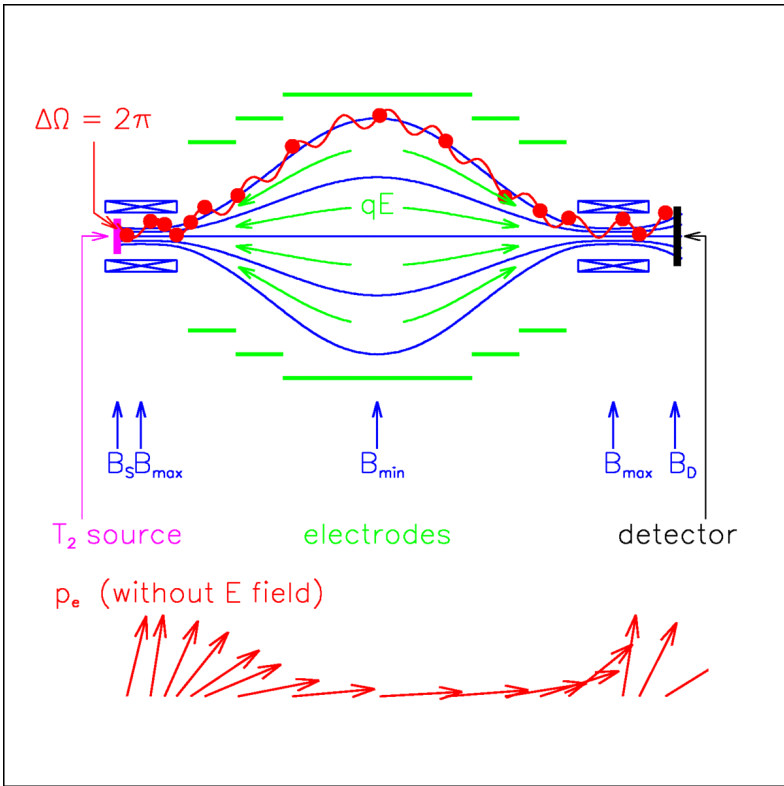
The KATRIN experiment



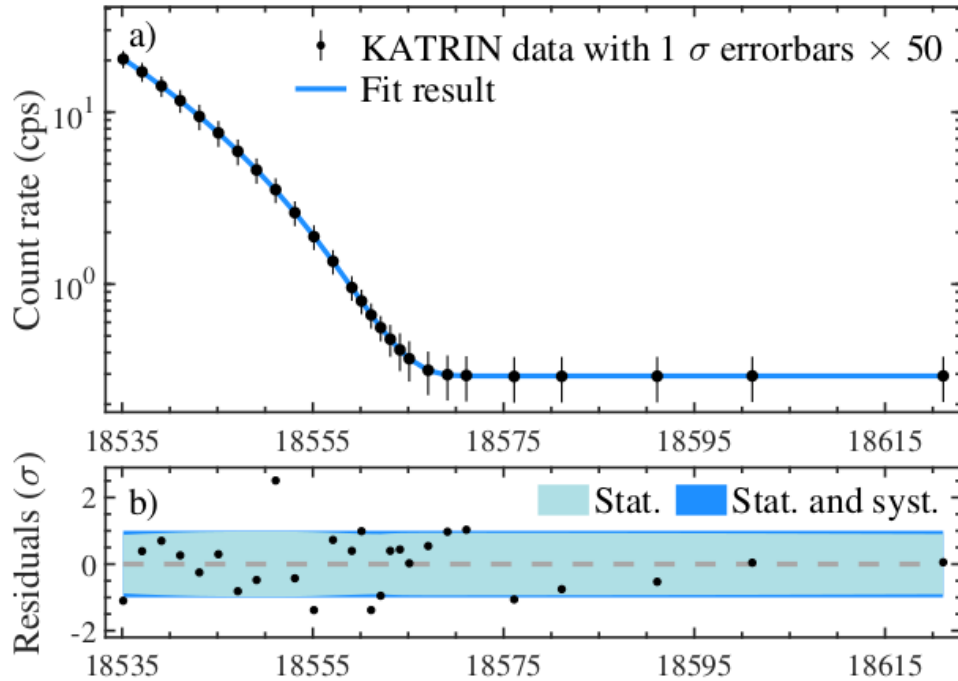
The Karlsruhe TRITium Neutrino experiment



MAC-E Filter



Features and results



Best experimental limit on neutrino mass

$$m_e < 1.1 \text{ eV (95\% CL)}$$

Sensitivity (5 years) $\sim 0.2 \text{ eV}$ (limited)

CNB target:

Gaseous target, only $\sim 0.2 \text{ mg}$

$\rightarrow 10^{-6}$ events/year

Requirements for CNB detection

- **Large target, 100 g (10 events/year)**
- **Very low target induced smearing**
- **High rate ($\sim 10^{14}$ Bq) handling**
- **Filter compression (~ 1 m size)**
- **High resolution electron detection (0.05 eV)**

The PTOLEMY project

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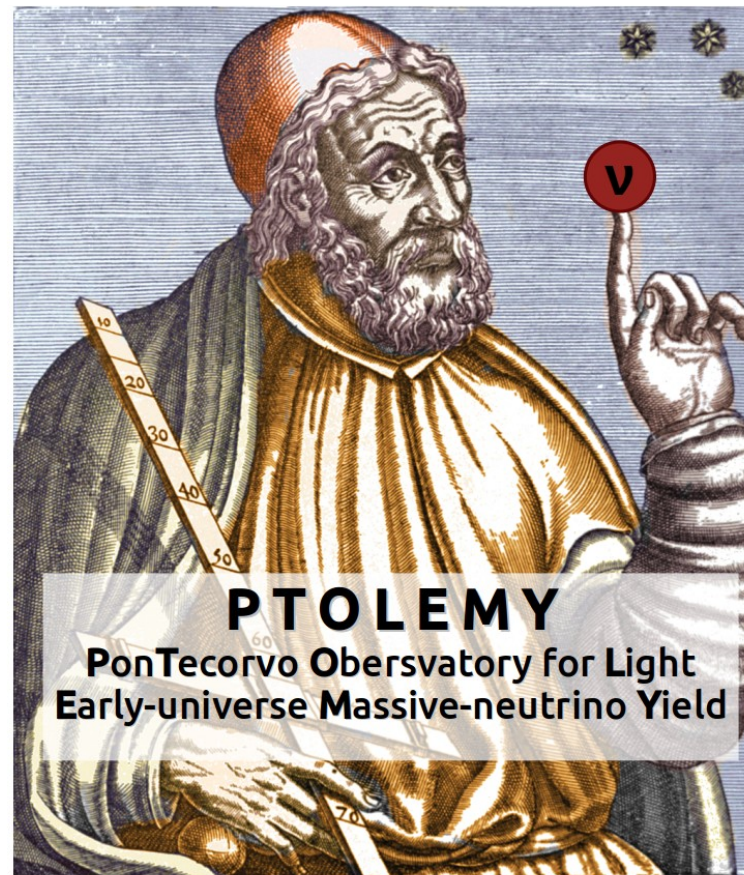
²⁶Università degli Studi di Pisa, Pisa, Italy

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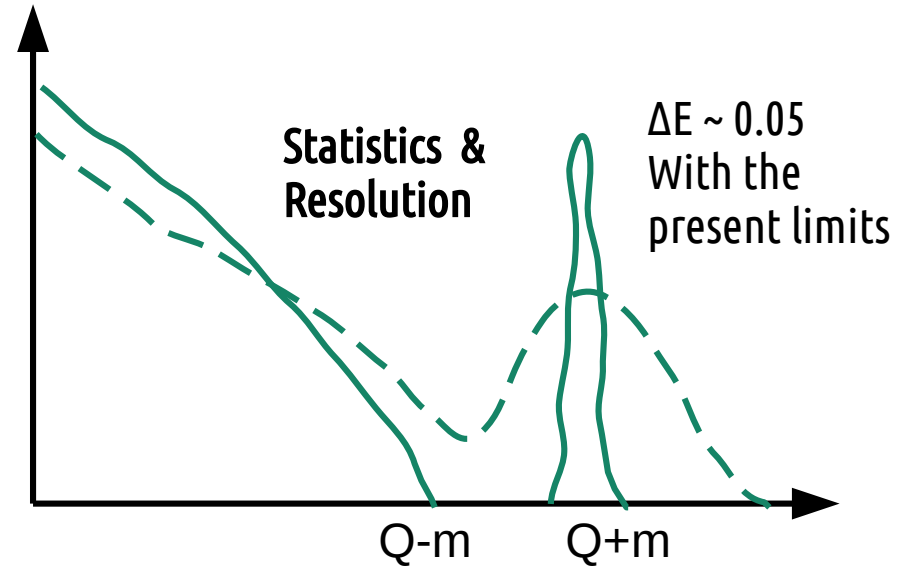
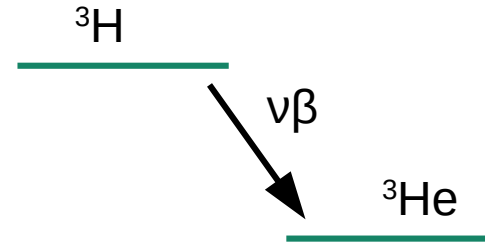
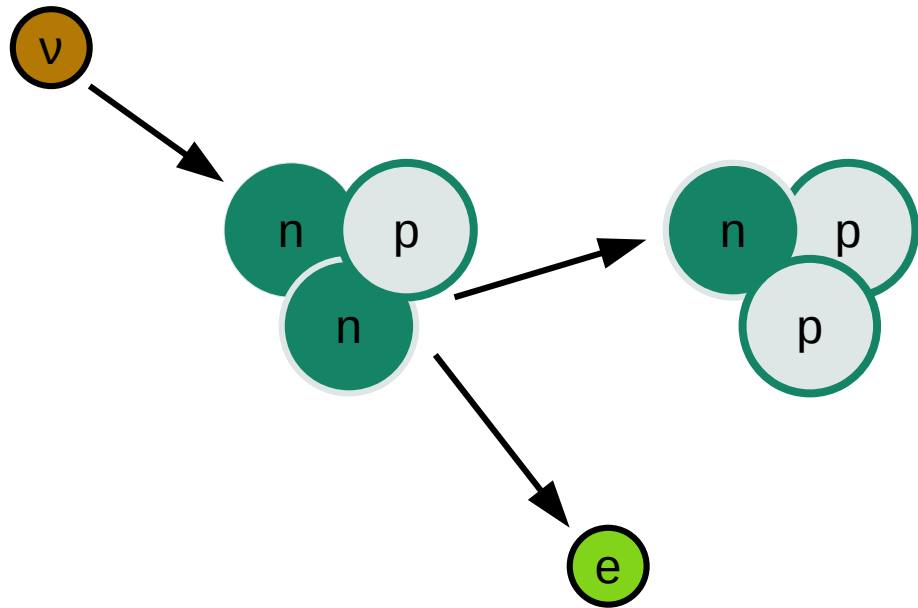
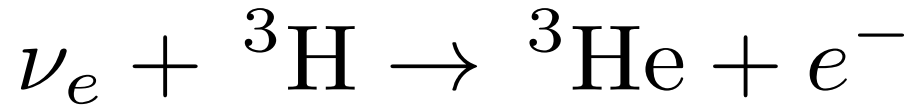
²⁹Gran Sasso Science Institute (GSSI), L'Aquila, Italy

³⁰Johannes Gutenberg-Universität Mainz, Germany

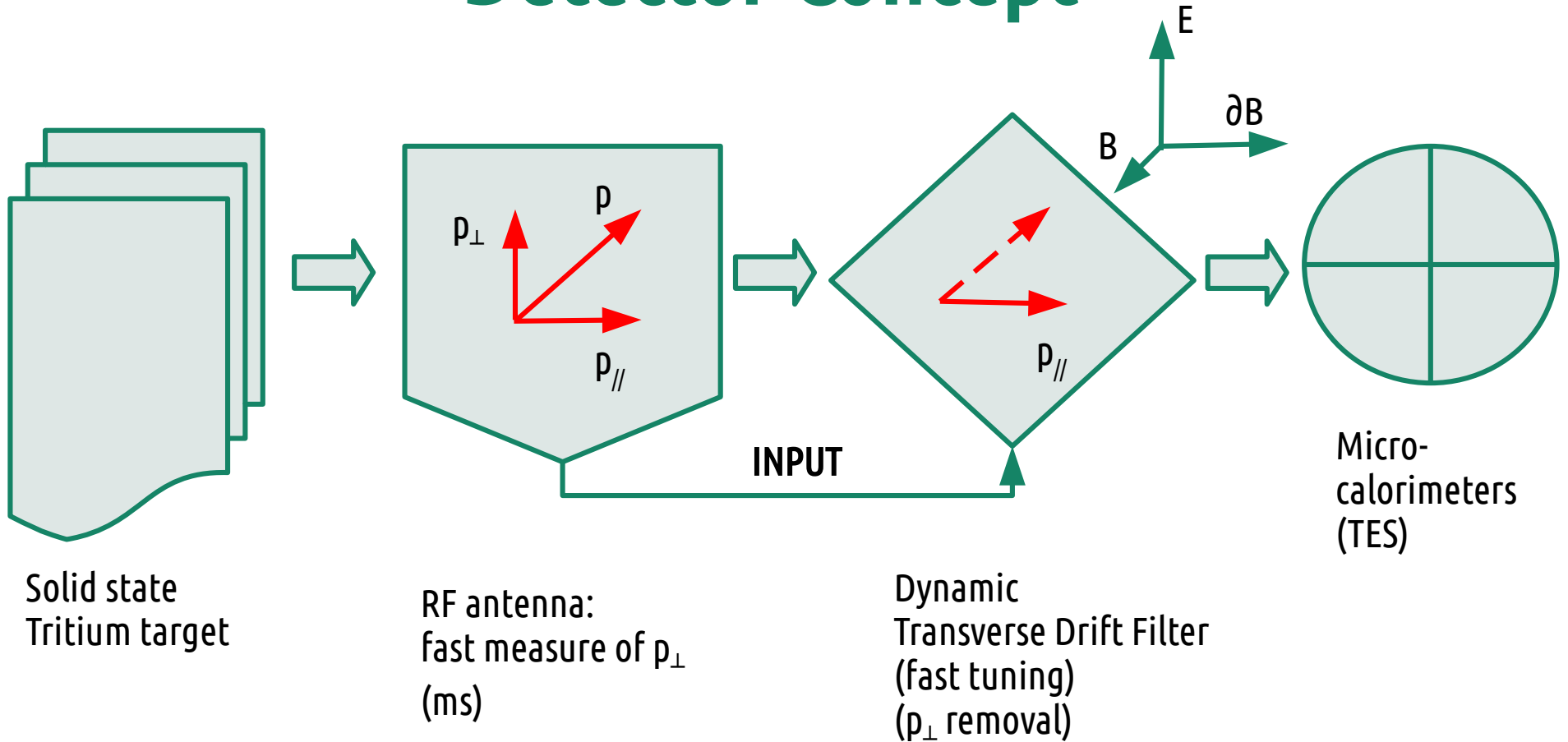


[M.G. Betti et al., 2019]

Detection Principle – CNB on ${}^3\text{H}$

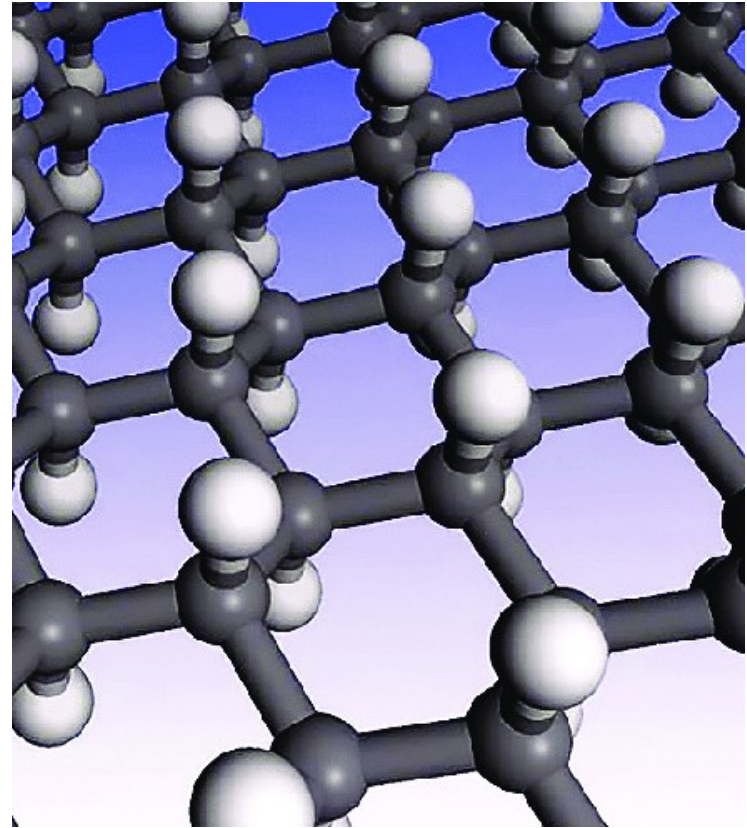


Detector Concept

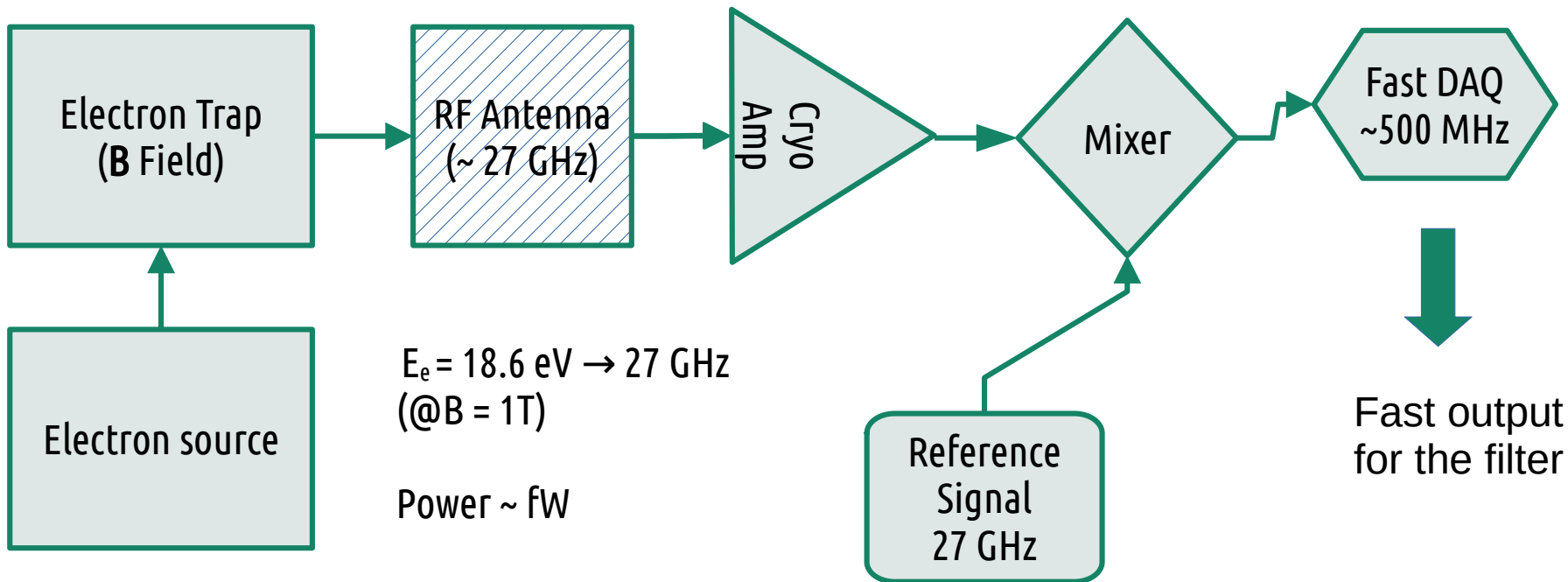


Target: tritiated graphene

- **Single atomic layer 2D (sp^3), single sided**
- **Binding energy (<3 eV), measurable**
- **$0,2 \text{ mg/m}^2$ (1 KATRIN/ m^2 !!!)
(2 Ci/m^2)**



RF Antenna R&D



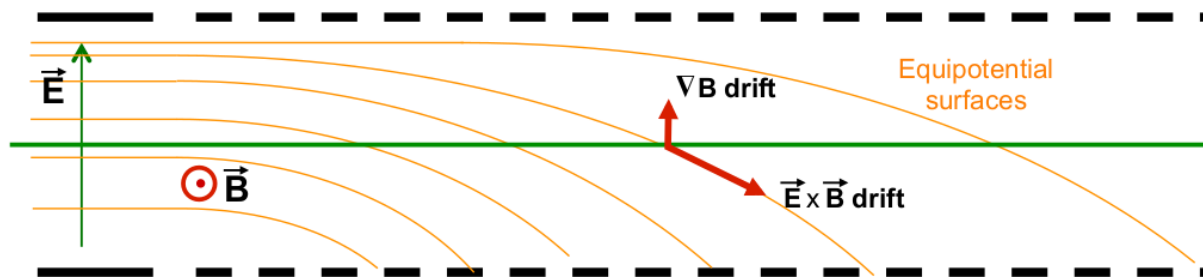
RF R&D at LNGS



Electron Gun

RF cryogenic system

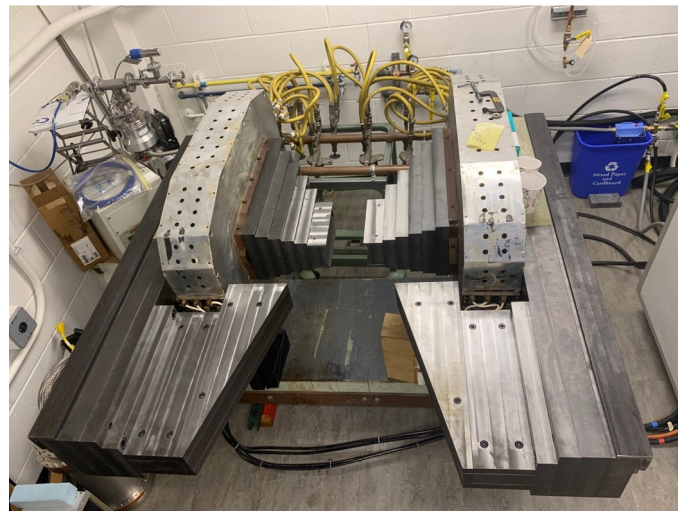
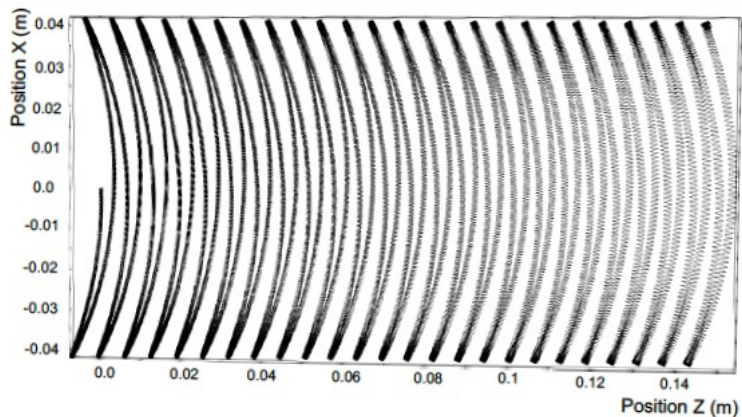
Transverse Drift Filter



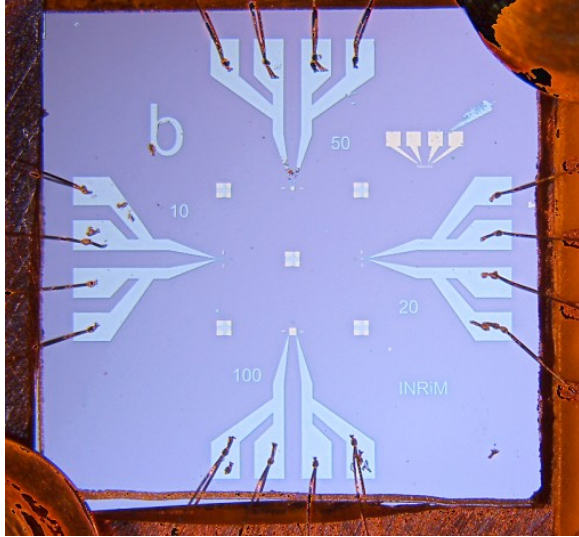
[M.G. Betti et al, 2019;
A. Apponi, 2021]

Top view

negative potential walls



Electron detectors (TES)

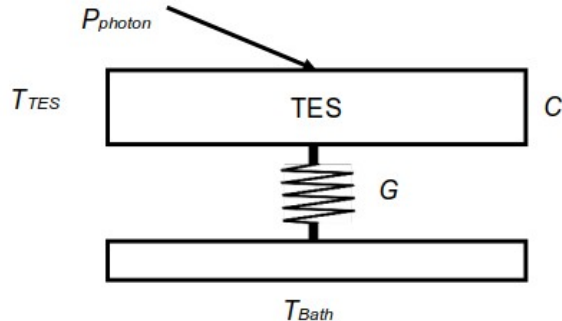


Criogenic Transition Edge Sensors (TES)

TiAu TES (under test)

- Cold bath at 50 mK
- large area ($50 \times 50 \mu\text{m}^2$) (pixel)
- fall time $47 \mu\text{s}$
- very small thickness for 100 eV electrons
- resolution better than $\Delta E = 0.05$ at $E = 100$ eV

$\Delta E = 0.16$ eV already achieved for 1540nm IR



Filter Prototype

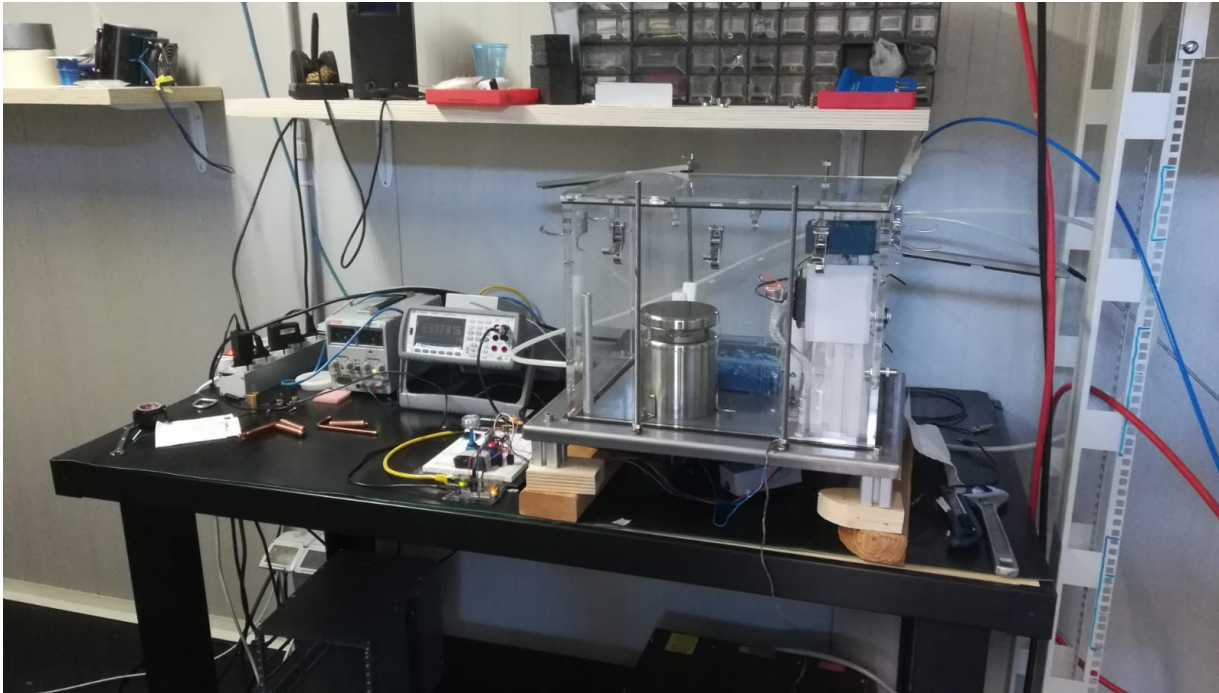


EM Filter prototype

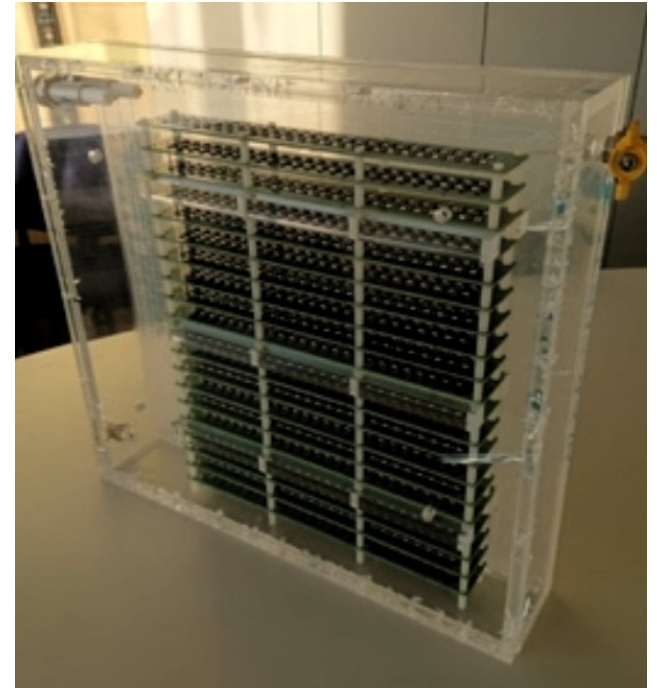


Cryo system

High precision HV R&D



Field mill HV measure



Diodes' stabilizer

Possible sites (shallow depth)



Mt. Soratte Bunker
North Rome
Overburden ~300-400 m
[A. Candela et al., 2021]



Predappio Bunker
Emilia Romagna
Overburden ~50-70 m

Ptolemy schedule

- **Conceptual design report, 2023**
- **Ptolemy Demonstrator, 0.1 mg source (Neutrino mass), 2025**
- **Full scale experiment (> 2030)**
 - Graphene packaging
 - Modular detector

Conclusions

- Goal **detection of the CNB**, very early universe, with tritium source on graphene
- A new and rich **window on Big Bang Cosmology**
- **Neutrino mass** (by product)
- **Majorana vs Dirac**
- Many **challenging aspects**
 - large target
 - excellent energy resolution
 - filter compression

Collaborators and ideas are welcome!



**Thank you
very much!**