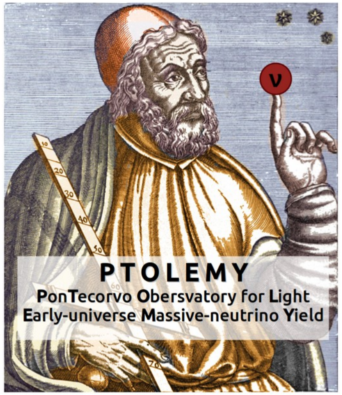
Detection of Cosmic Neutrino Background with the "PTOLEMY" experiment



SEMINARIUM
ASTROFIZYCZNE
WFAIS UJ oraz Komisji Astrofizyki PAU
Jagiellonian University, Dec 22th 2021

INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

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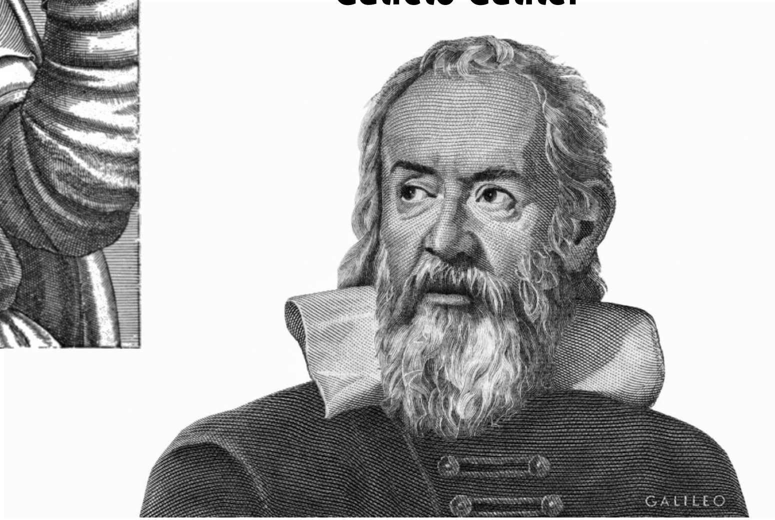
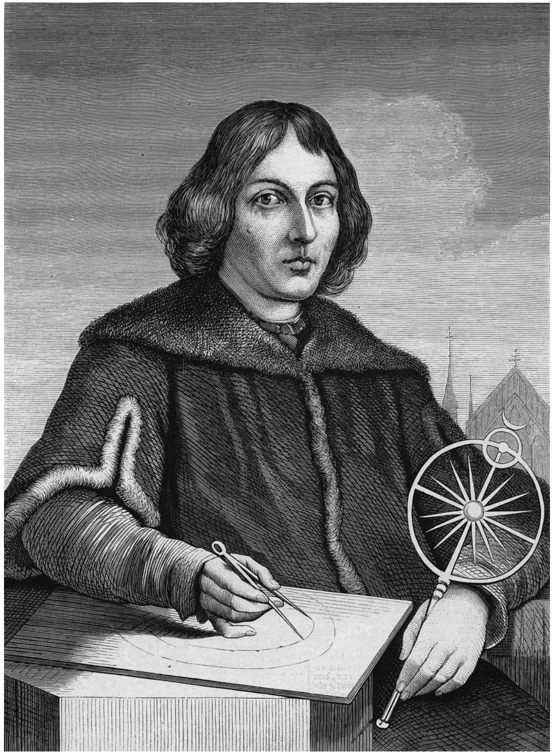
Dialogue Concerning the Two Chief World Systems

Claudius Ptolemaeus

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

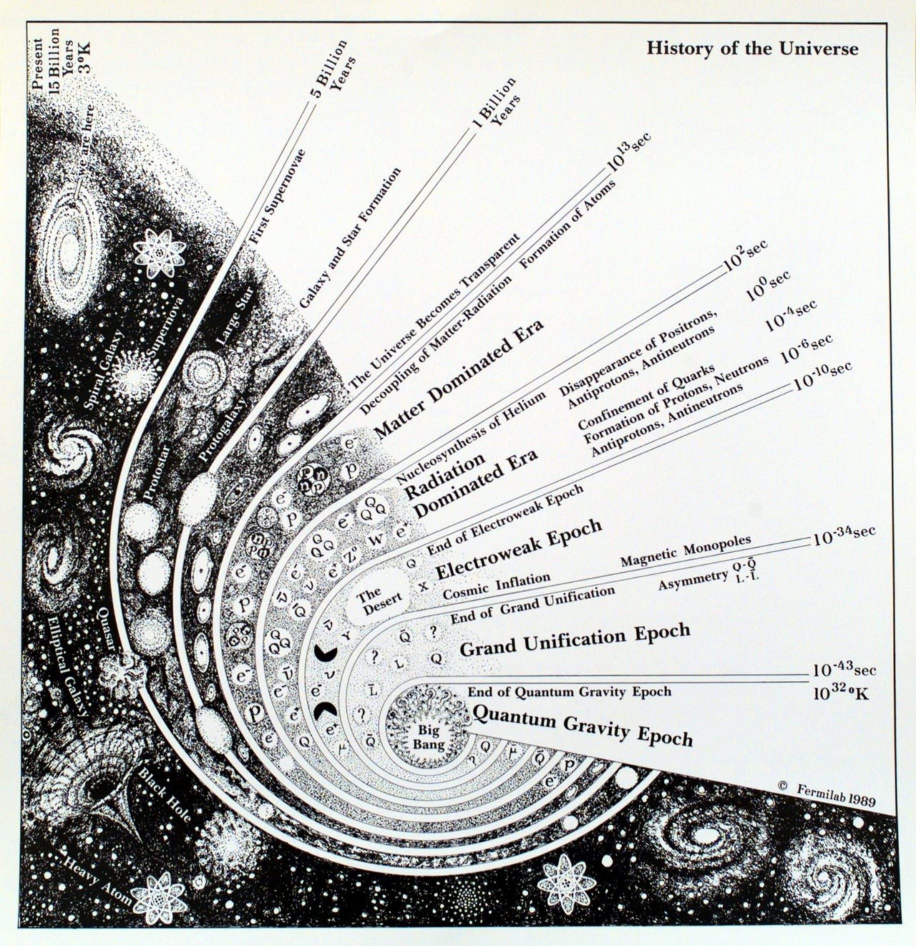
Galielo Galilei





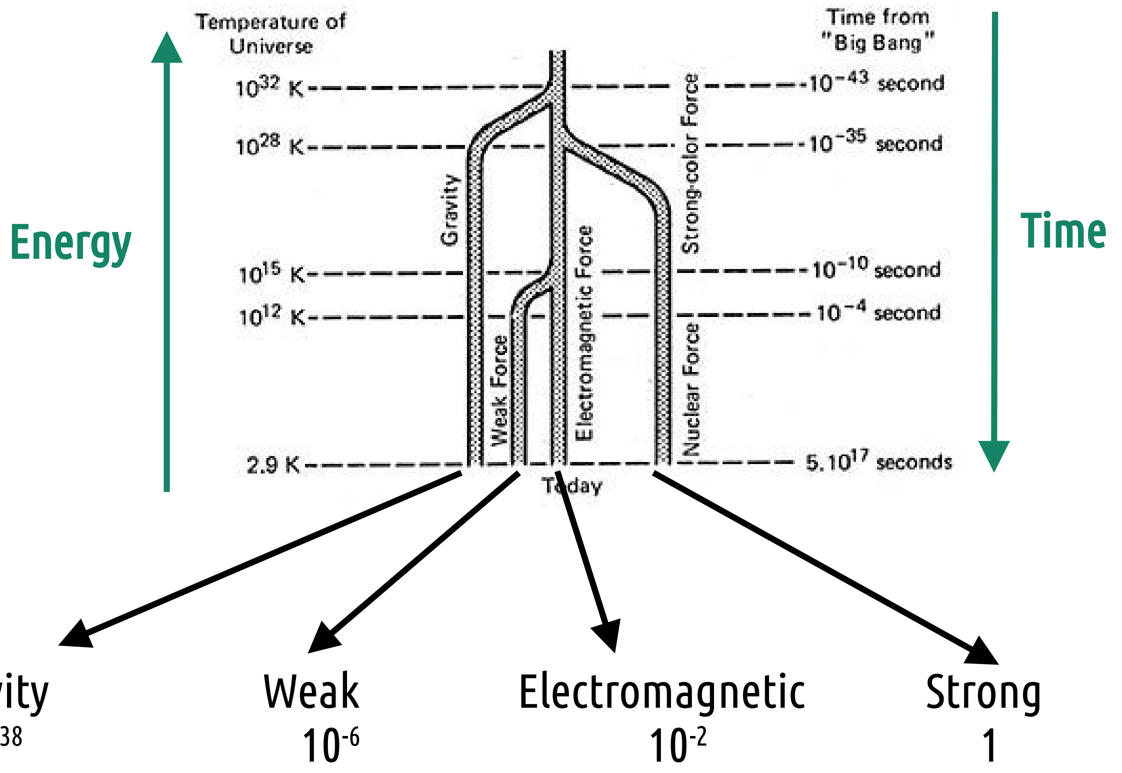
Nicolaus Copernicus

Today's Chief Wold System 2/2

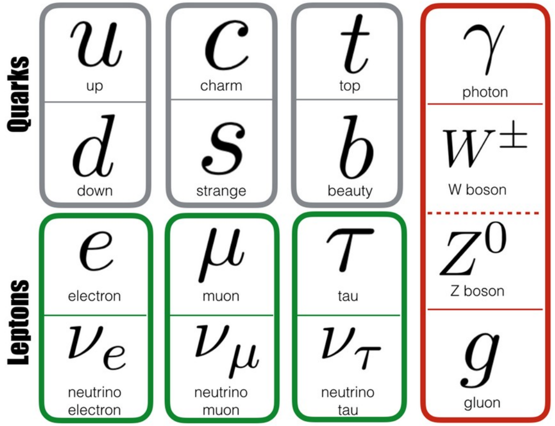


The Big Bang
emergence of the present universe from an ultra-dense and high-temperature initial state

Four interactions from One (?)



Forces & Particles



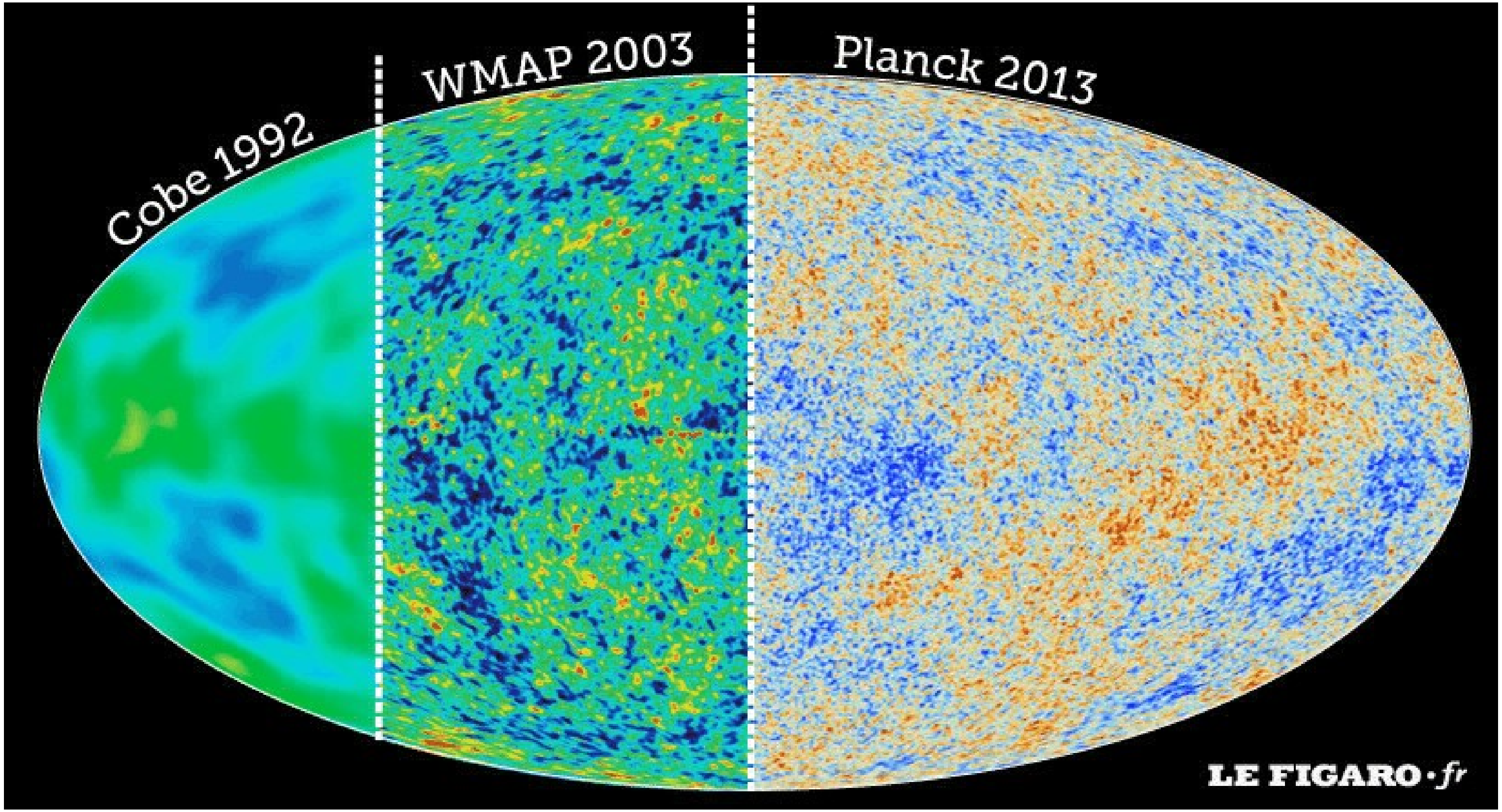
Main evidences in favor

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

Important issues

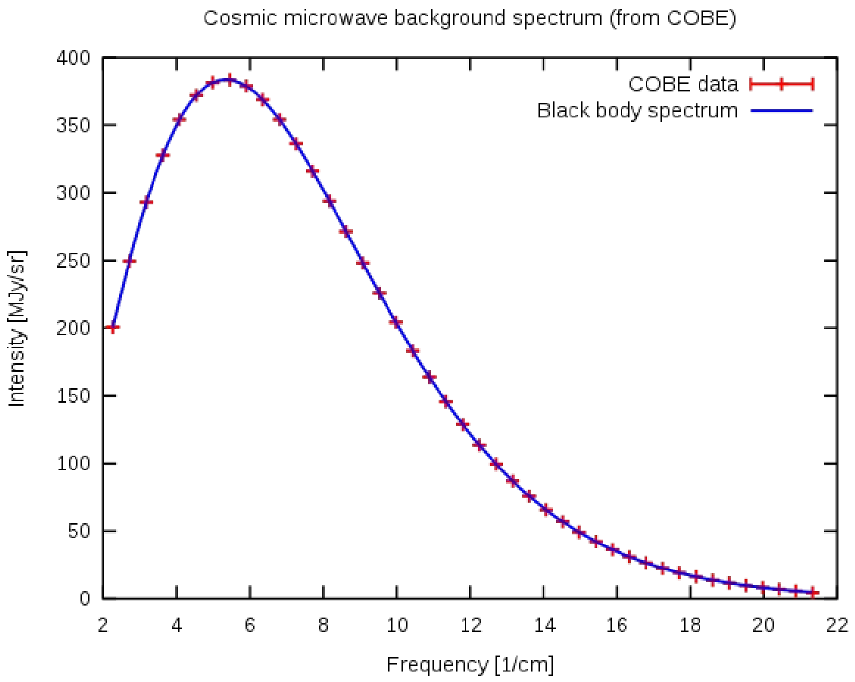
- **Baryon asymmetry,** $\eta = 10^{-10}$
- **Dark** energy (~70%) and **dark matter** (~25%) still unknown
- **Horizons** and **flatness** problem: cosmological constant and inflation

The gold mine of cosmologists

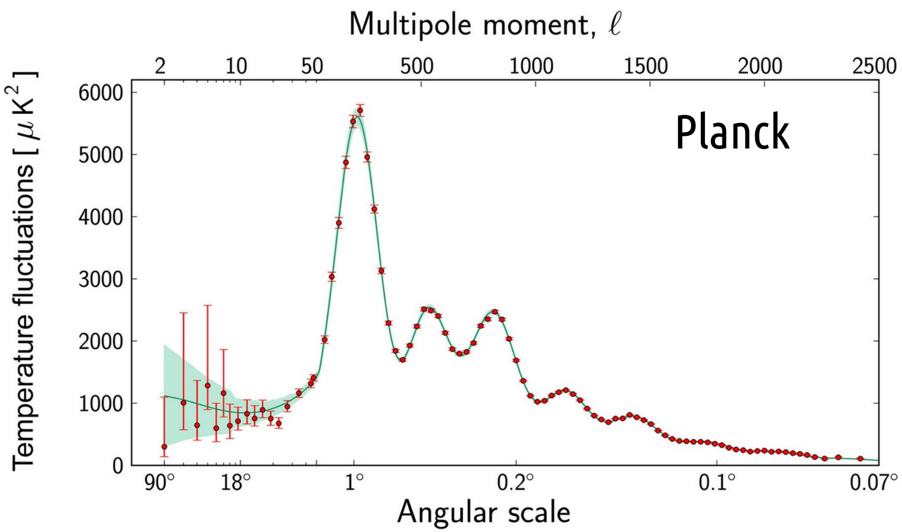


CMB: The oldest electromagnetic radiation in the universe

Cosmic Microwave Radiation

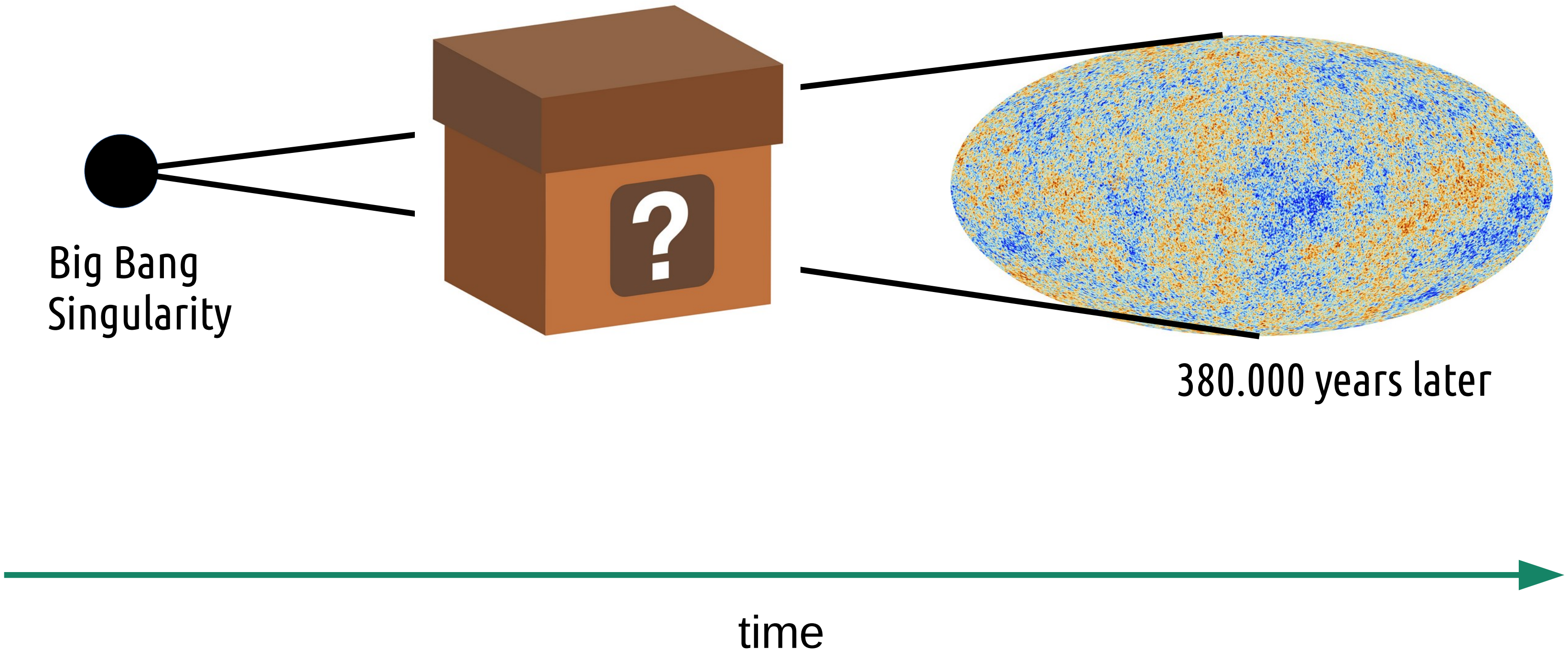


Balck body radiation
T = 2.75 K



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

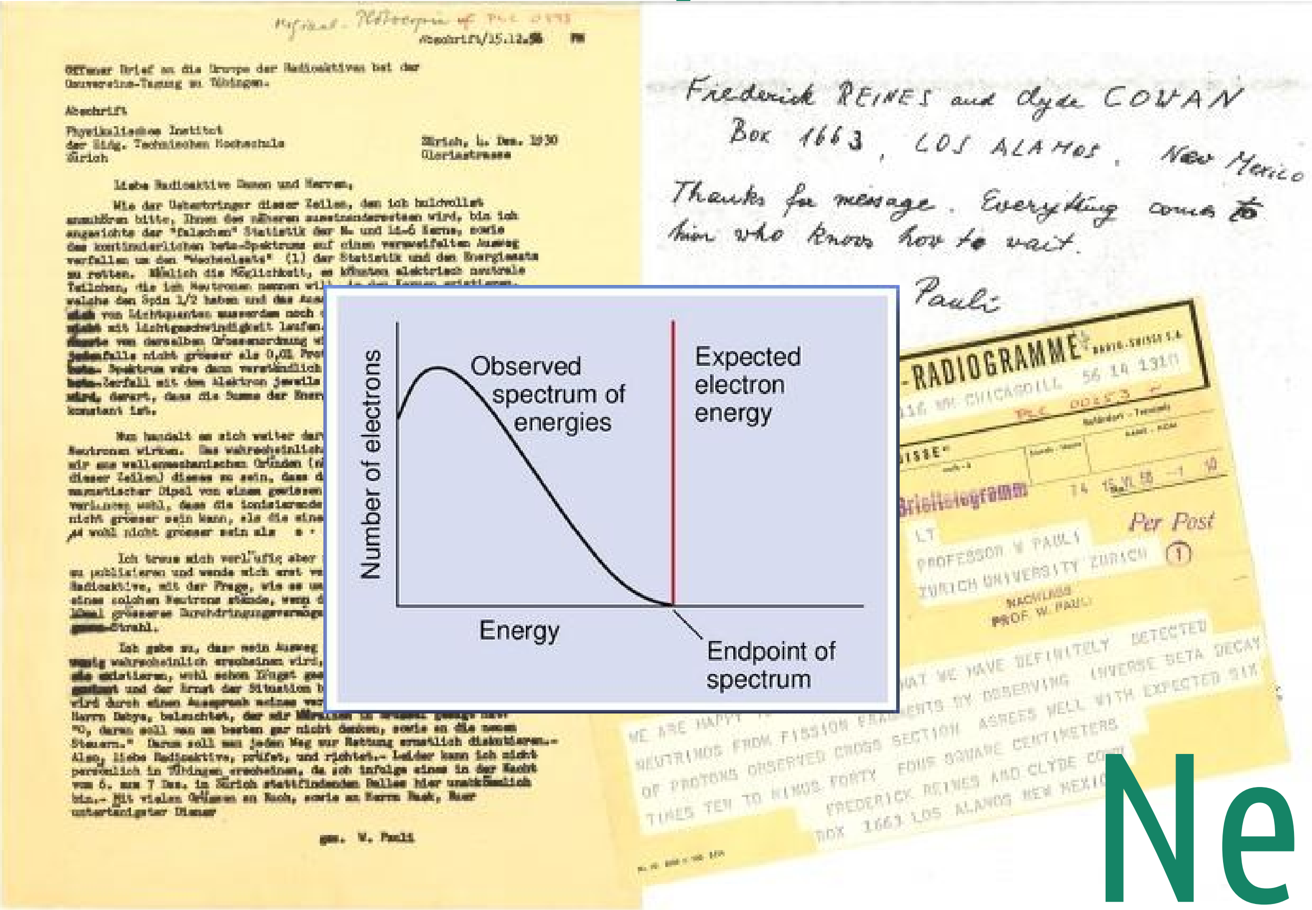
Is there anything older than CMB?



A more precious mine: at the very early universe

Cosmic Neutrino Background,only 1s after the beginning

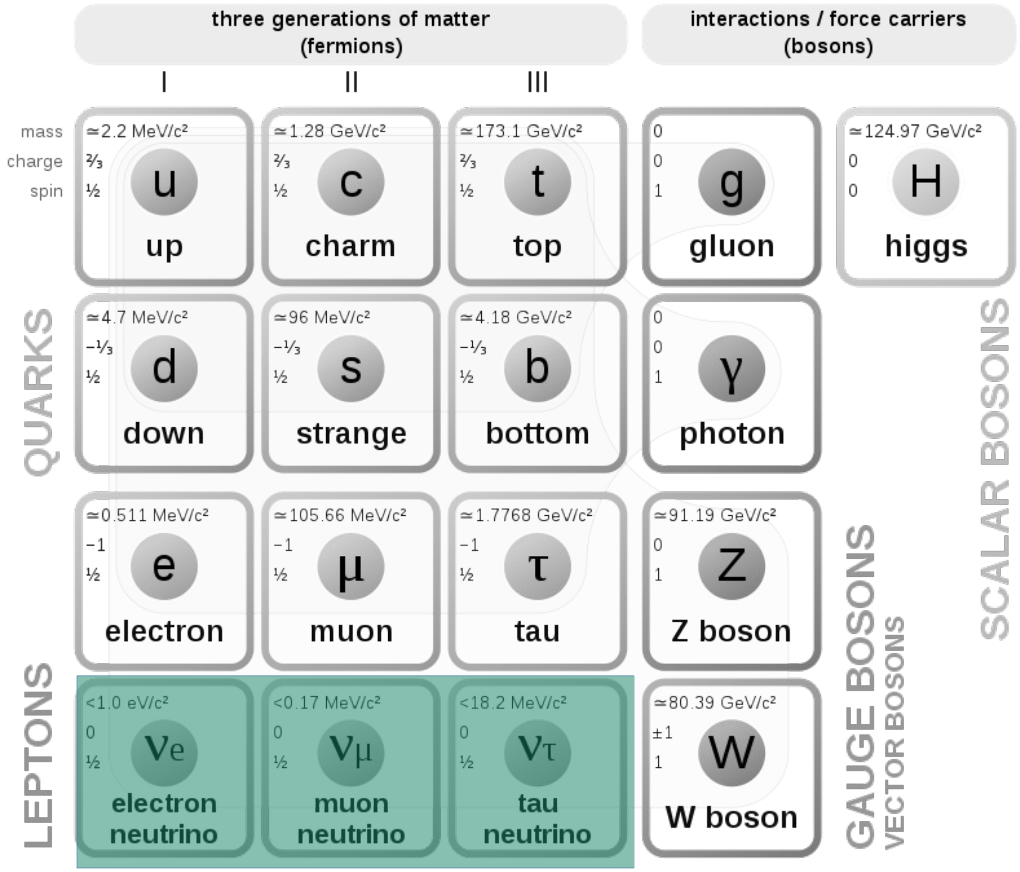
The oldest particle of the universe



Wolfgang Pauli, 1930

Neutrinos

Neutrinos and Standard Model

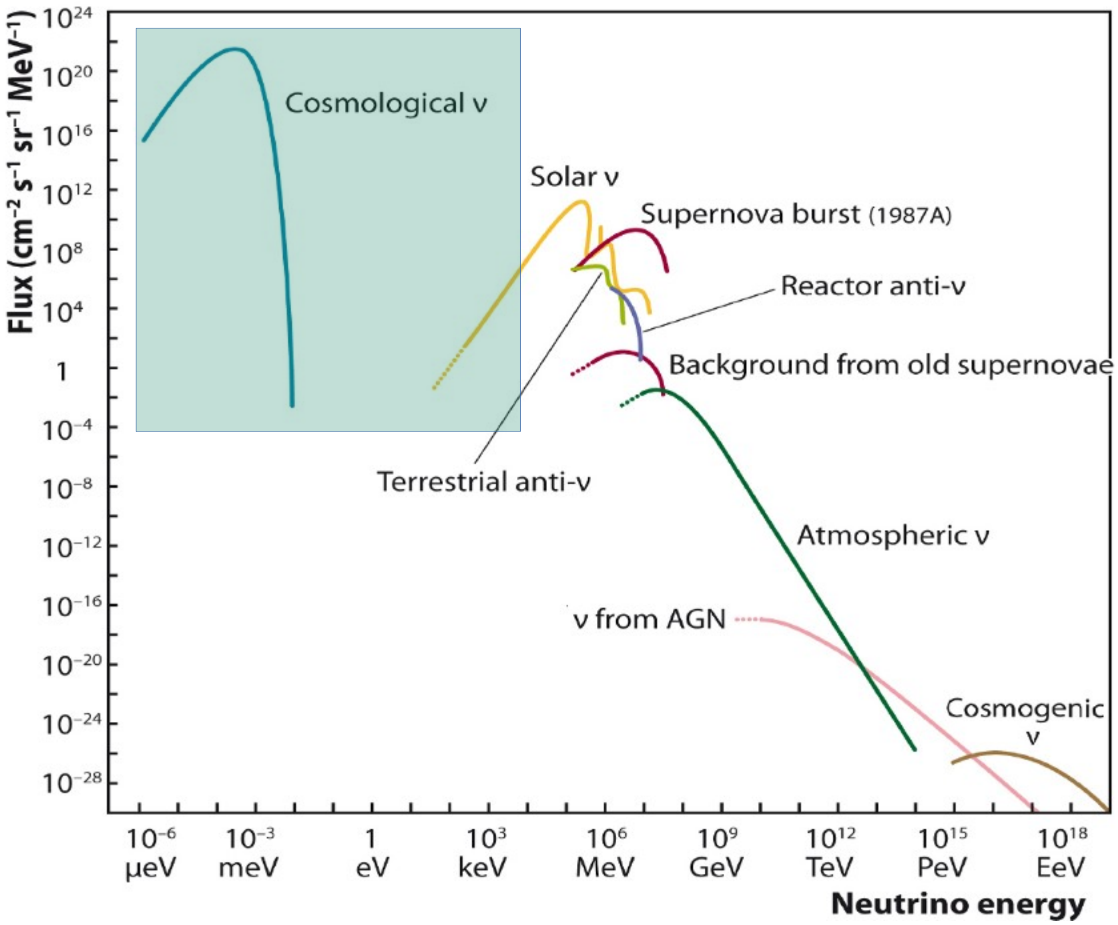


– low interaction probability $\sigma \sim 10^{-44}$ cm^2

- **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

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Reactor Solar

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

Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}, $\lvert\Delta m^2_{31,32}\rvert$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\lvert\Delta m^2_{31,32}\rvert$, θ_{13},$\delta_{\rm CP}$
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\lvert\Delta m^2_{31,32}\rvert$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	$\delta_{\rm CP}$	θ_{13} , θ_{23}

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

The nature was so kind

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

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

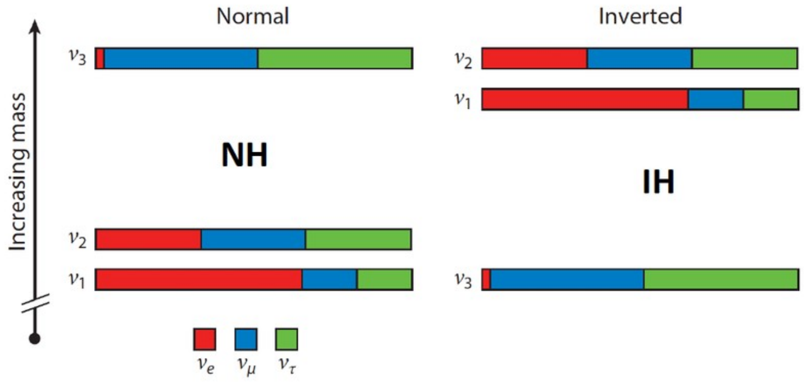
$\vartheta_{12} \sim \vartheta_{23}$ large

ϑ_{13} small

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

Neutrino mass

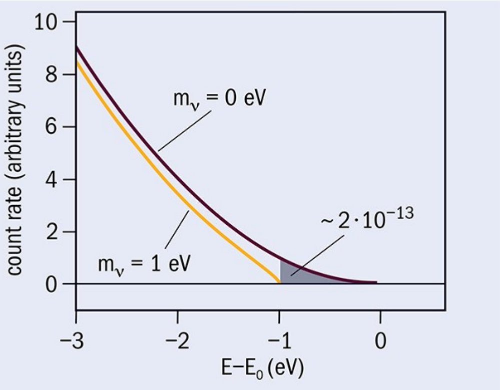
ordering



1. KATRIN experiment

From beta decay

$m_{\nu e} < 1.1$ eV (95% CL)
[M. Aker et al., 2019]



Tritium beta decay

2. Cosmology

$S = \Sigma\, m_i$
$m_\nu < 50$ meV

Ω_ν

CNB or CνB or Relic Neutrinos

- From ~ **1 s** old universe
- T = 1.95 K
- E ~$10^{-6} \div 10^{-4}$ eV
- Strong **indirect evidence** from Cosmology:
  BBN (D, ^{4}He), CMB → 3ν and T_ν, …
- But… **no direct evidence yet**

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

Direct CNB search

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

Then:

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

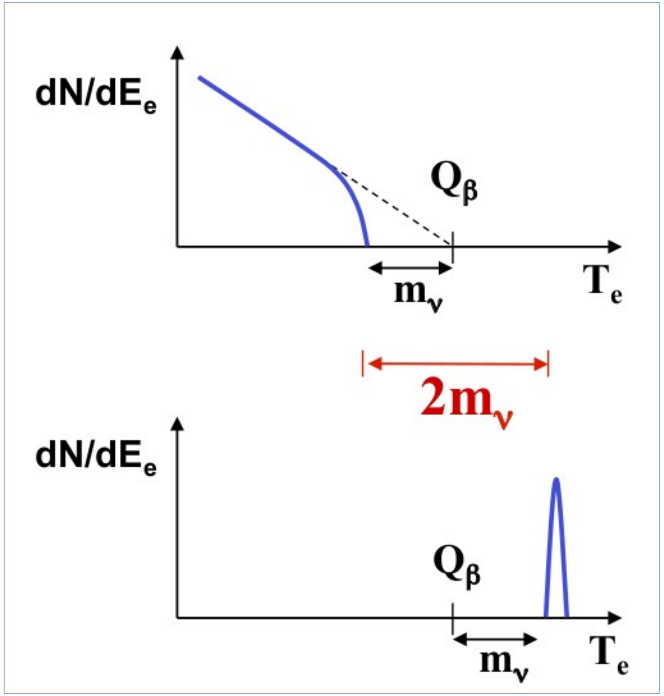
Neutrino Capture

- **Beta unstable** nucleus A
- **Treshold-less** reaction

  $\nu_e + A \rightarrow B + e^-$

- **Monocromatic** peak at $Q+m_\nu$
- Neutrino **mass as by product** from the CNB detection!

  [A. Cocco et al, 2007]

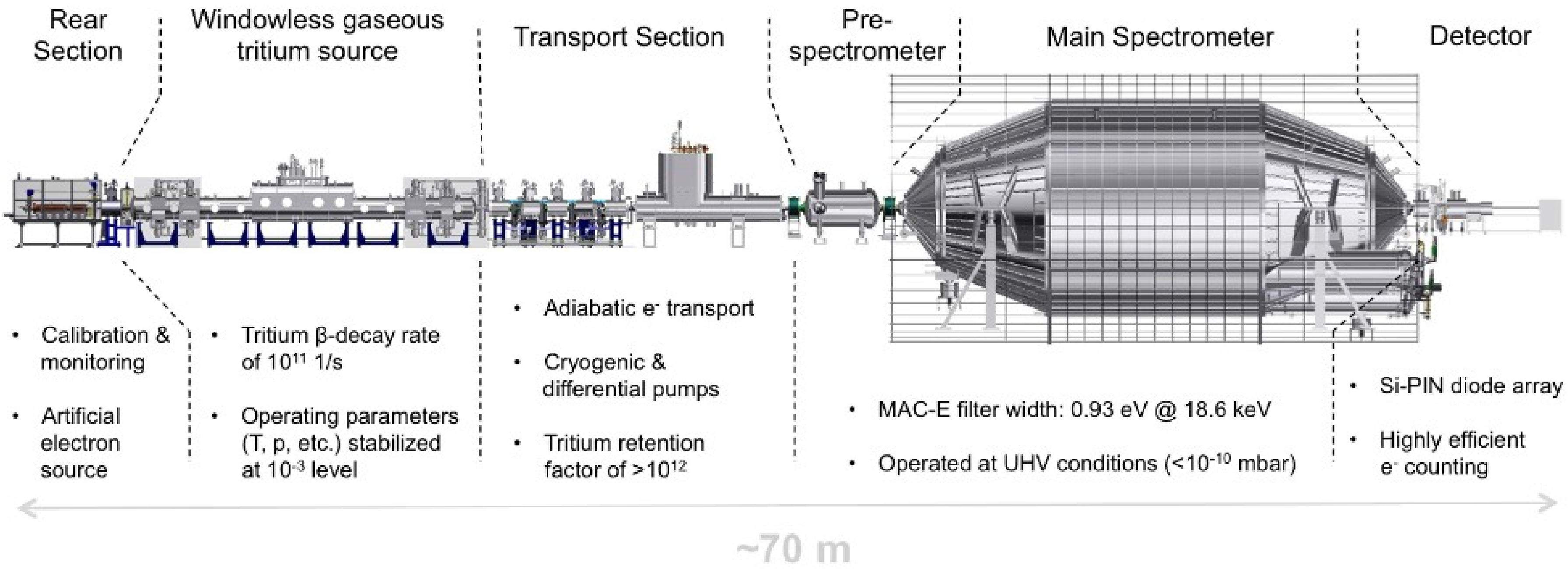


Tritium: the best candidate

- **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)

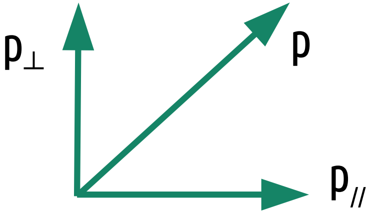
  $\sigma \sim 10^{-44}$ cm^2

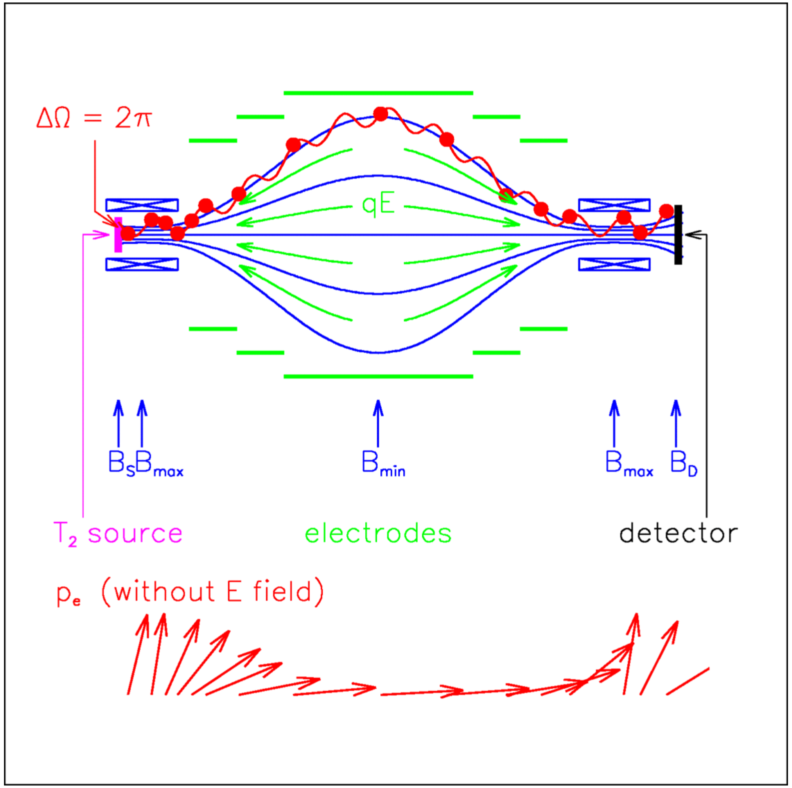
The KATRIN experiment



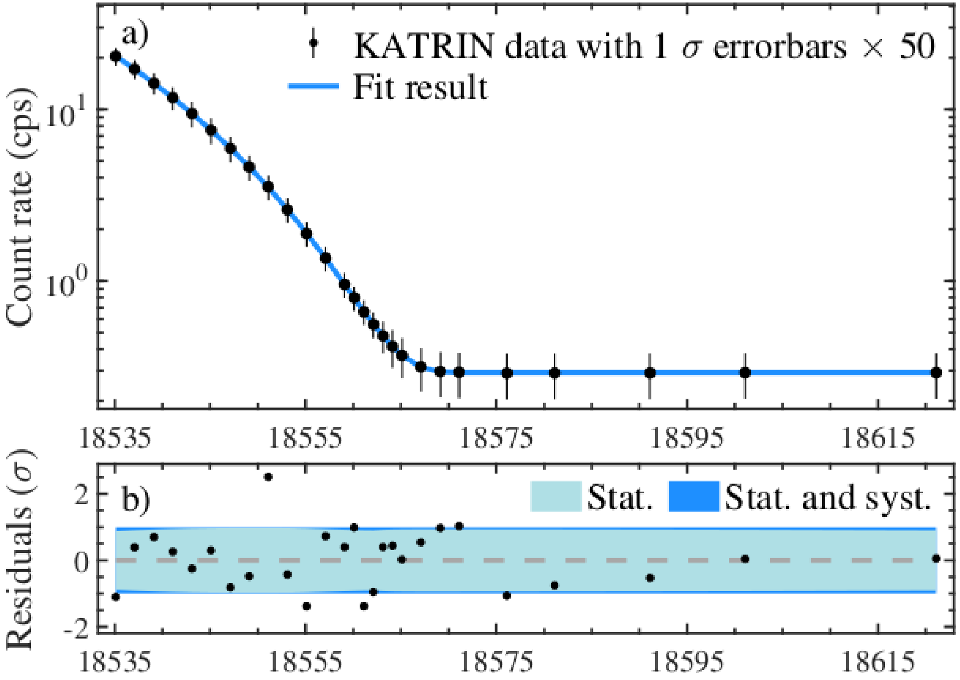
The **KA**rlsruhe **TRI**tium **N**eutrino experiment

MAC-E Filter


p⊥
p
p//


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 < 1.1 eV (95% CL)

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

CNB target:
Gaseous target, **only ~0.2 mg**
→ 10^{-6} events/year

Requirements for CNB detection

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

The PTOLEMY project

A. Apponi,[1,2] M.G. Betti,[3,4] M. Borghesi,[5,6] A. Boscá,[7] F. Calle,[7] N. Canci,[8] G. Cavoto,[3,4] C. Chang,[9,10] W. Chung,[11] A.G. Cocco,[12] A.P. Colijn,[13,14] N. D'Ambrosio,[8] N. de Groot,[15] M. Faverzani,[5,6] A. Ferella,[8,16] E. Ferri,[5] L. Ficcadenti,[3,4] P. Garcia-Abia,[17] G. Garcia Gomez-Tejedor,[18] S. Gariazzo,[19] F. Gatti,[20] C. Gentile,[21] A. Giachero,[5,6] Y. Hochberg,[22] Y. Kahn,[10,23] A. Kievsky,[24] M. Lisanti,[11] G. Mangano,[12,25] L.E. Marcucci,[24,26] C. Mariani,[3,4] J. Martínez,[7] M. Messina,[8] E. Monticone,[19,27] A. Nucciotti,[5,6] D. Orlandi,[8] F. Pandolfi,[3] S. Parlati,[8] J. Pedrós,[7] C. Pérez de los Heros,[28] O. Pisanti,[12,25] A.D. Polosa,[3,4] A. Puiu,[8,29] I. Rago,[3,4] Y. Raitses,[21] M. Rajteri,[19,27] N. Rossi,[8] K. Rozwadowska,[8,29] I. Rucandio,[17] A. Ruocco,[1,2] R. Santorelli,[17] C.F. Strid,[30] A. Tan,[11] C.G. Tully,[11] M. Viviani,[24,26] U. Zeitler,[15] and F. Zhao[11]

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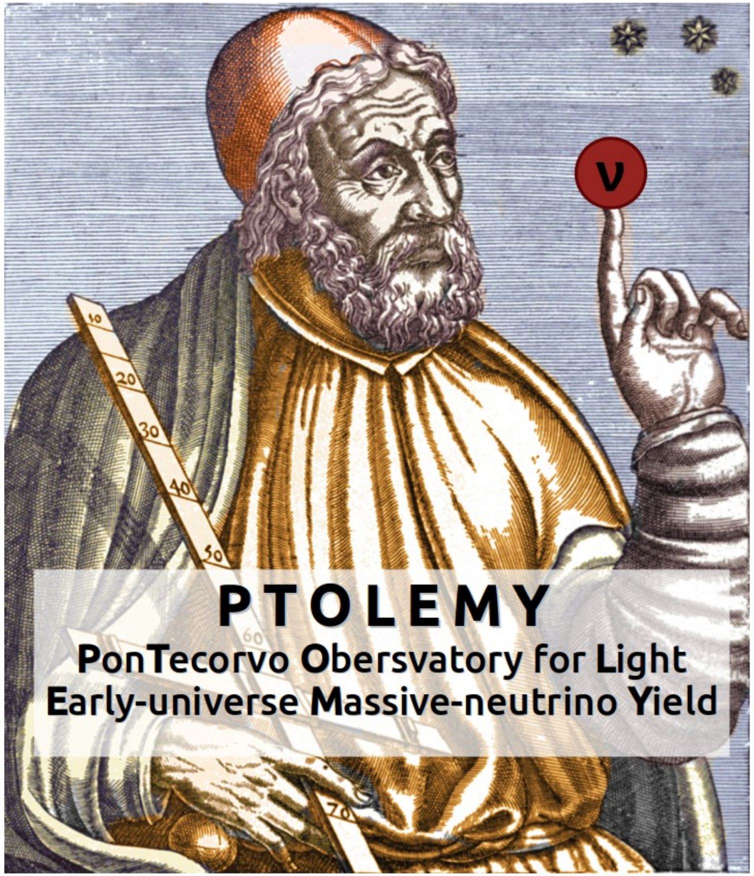
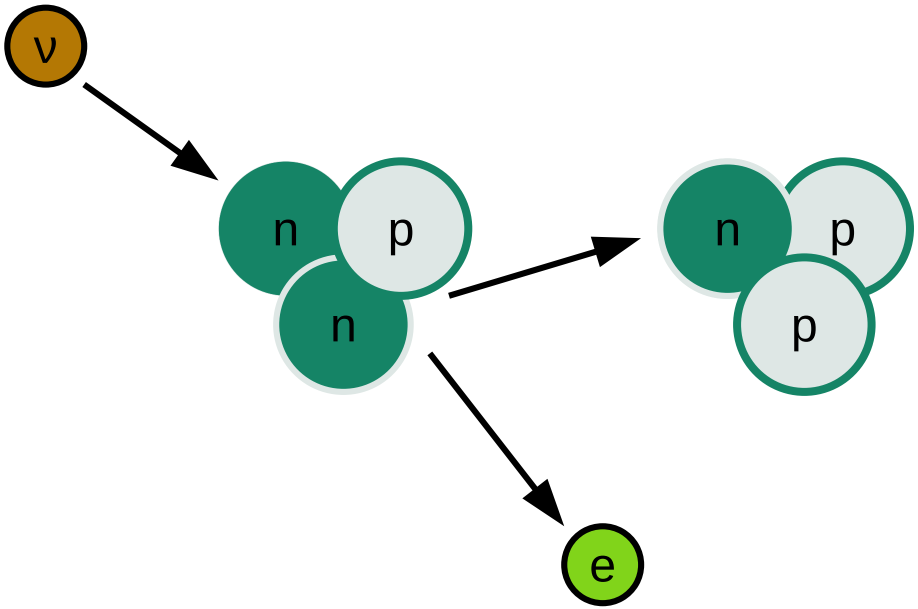
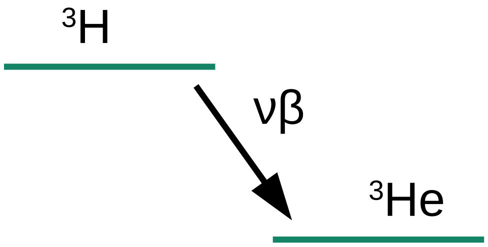
[M.G. Betti et al., 2019]

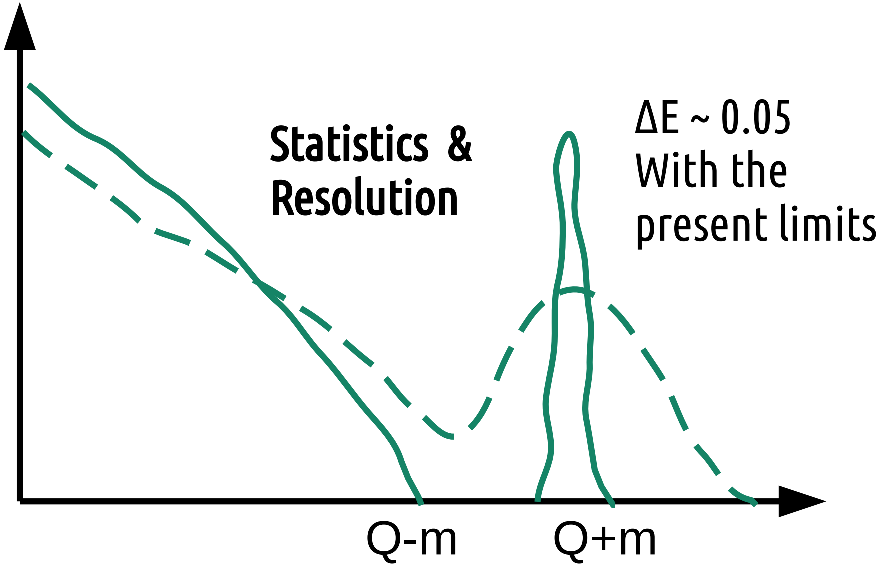


Detection Principle – CNB on ^3H

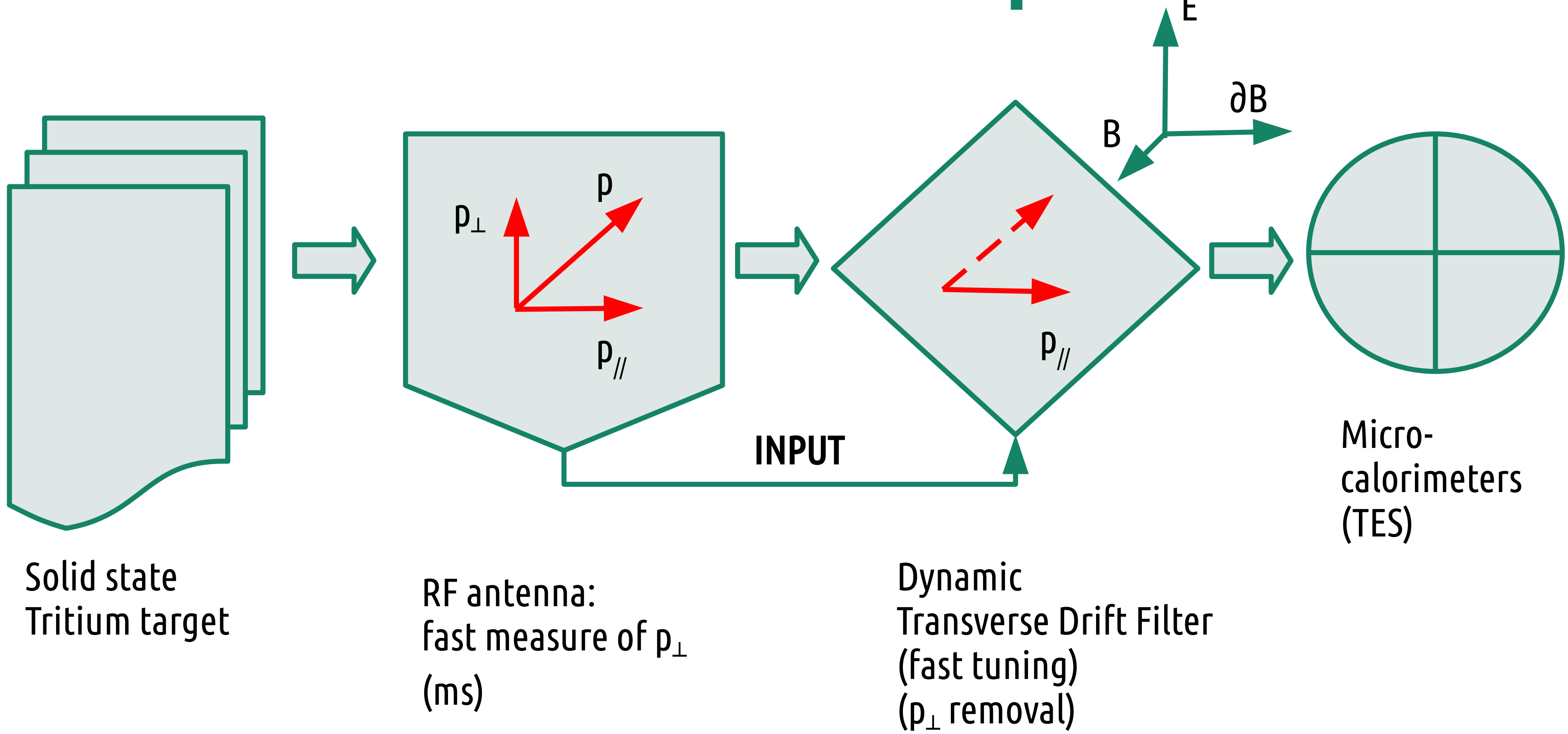
$$\nu_e + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^-$$





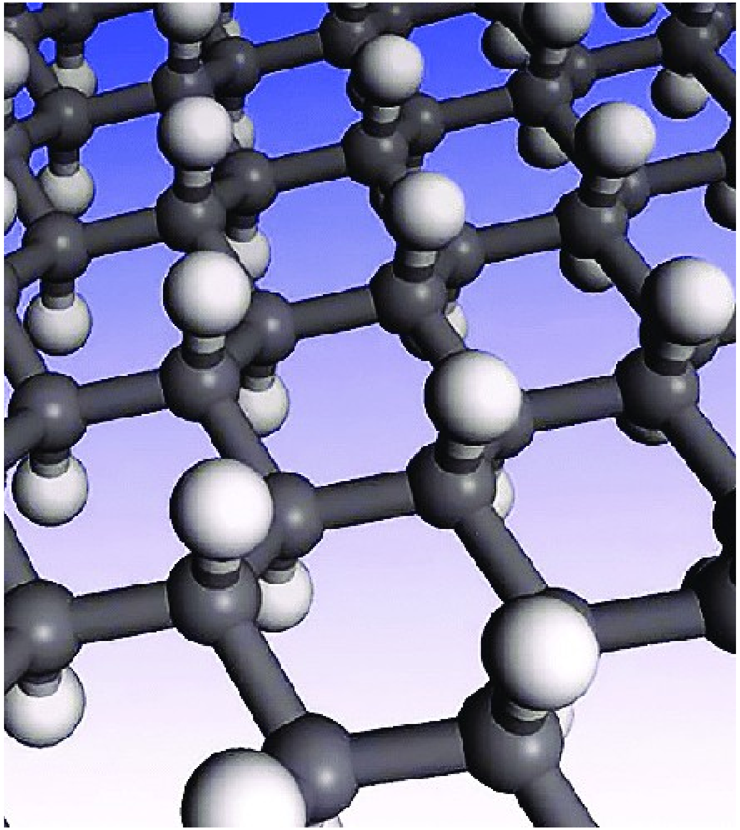


Detector Concept

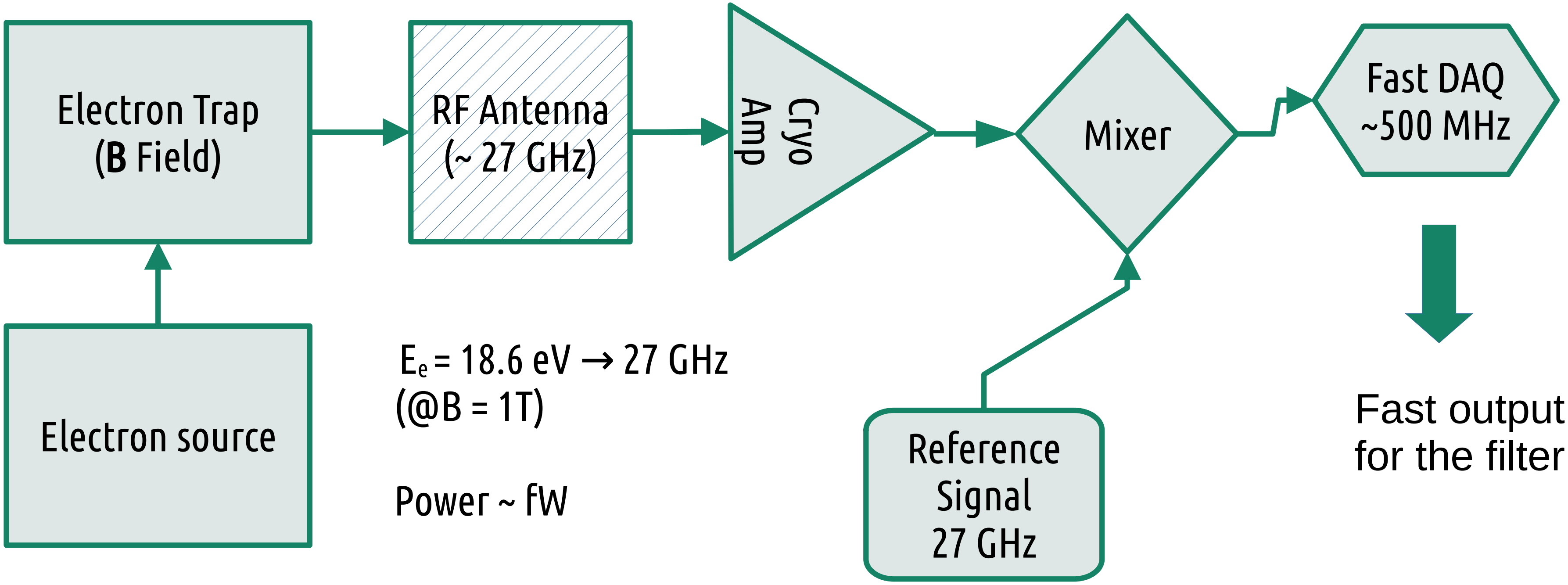


Target: tritiated graphene

- **Single atomic layer** 2D (sp^3), single sided
- Binding energy (<3 eV), measurable
- **0,2 mg/m²** (1 KATRIN/m² !!!) (2 Ci/m²)



RF Antenna R&D



E_e = 18.6 eV → 27 GHz
(@B = 1T)

Power ~ fW

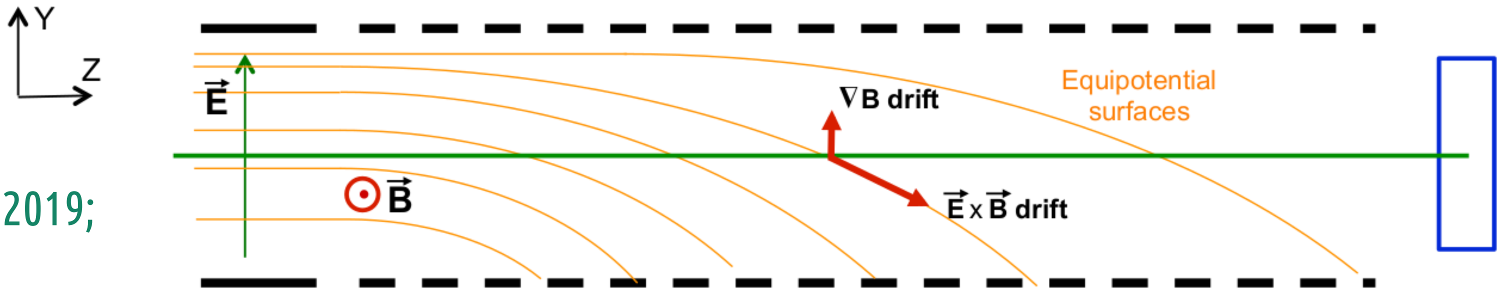
Fast output
for the filter

RF R&D at LNGS

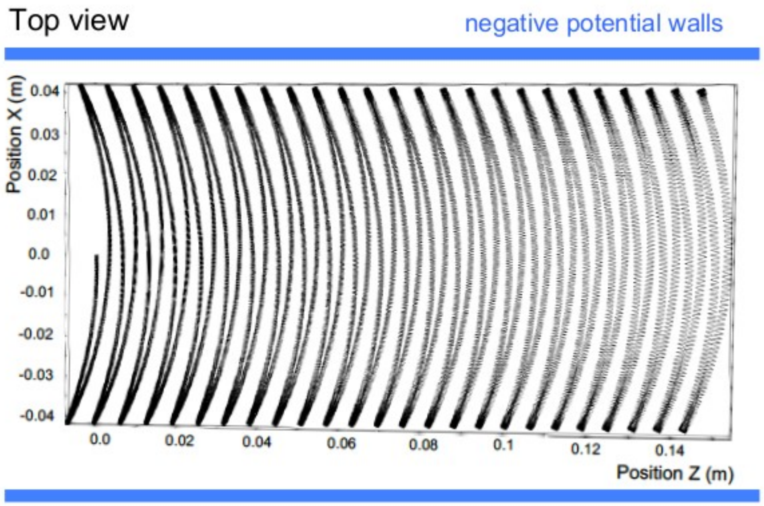
Electron Gun

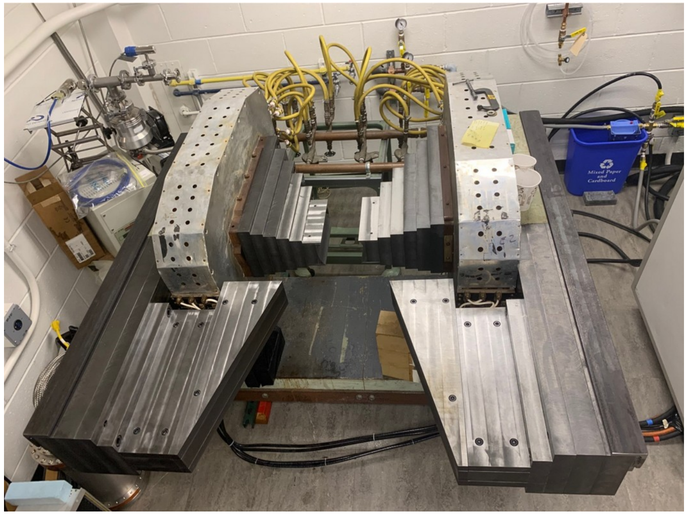
RF cryogenic system

Transverse Drift Filter

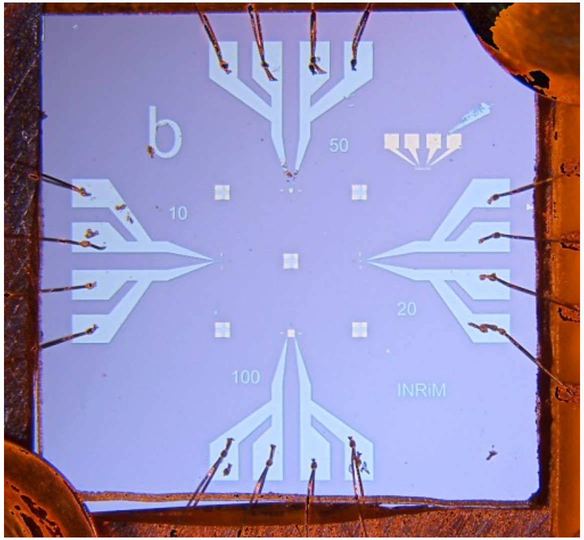


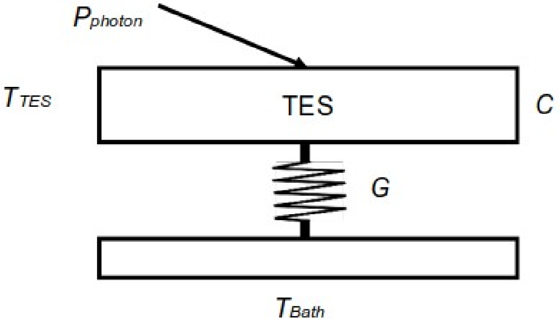
[M.G. Betti et al, 2019; A. Apponi, 2021]





Electron detectors (TES)





Criogenic **T**ransition **E**dge **S**ensors (TES)

TiAu TES (under test)

– Cold bath at 50 mK
– large area (50 x 50 μm^2) (pixel)
– fall time 47 μs
– very small thickness for 100 eV electrons
– resolution better than ΔE = 0.05 at E = 100 eV

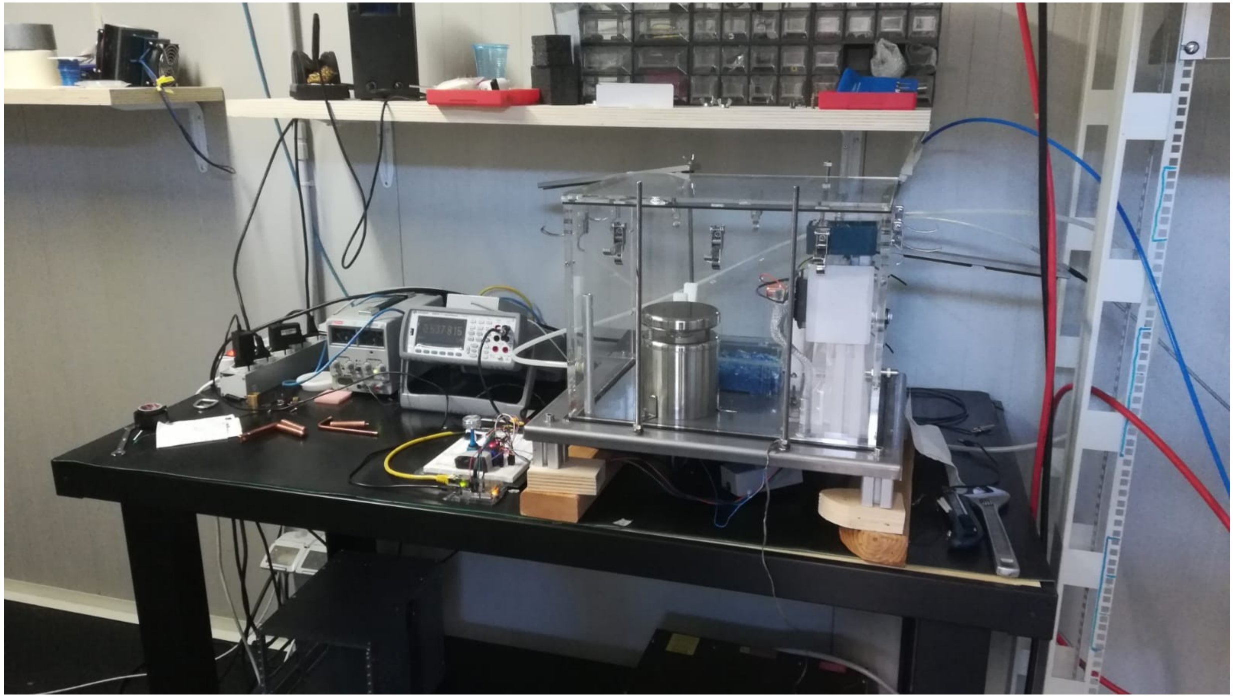
ΔE = 0.16 eV already achieved for 1540nm IR

Filter Prototype

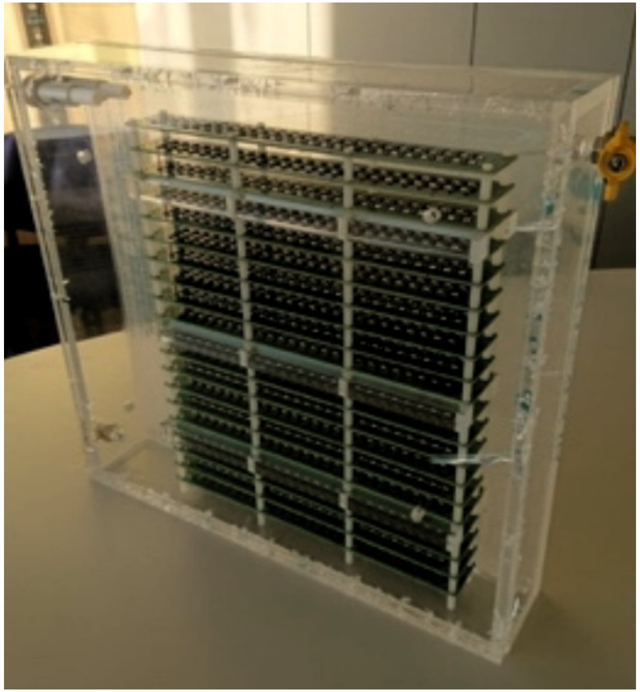
EM Filter prototype

Cryo system

High precision HV R&D



Field mill HV measure



Diods’ 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!