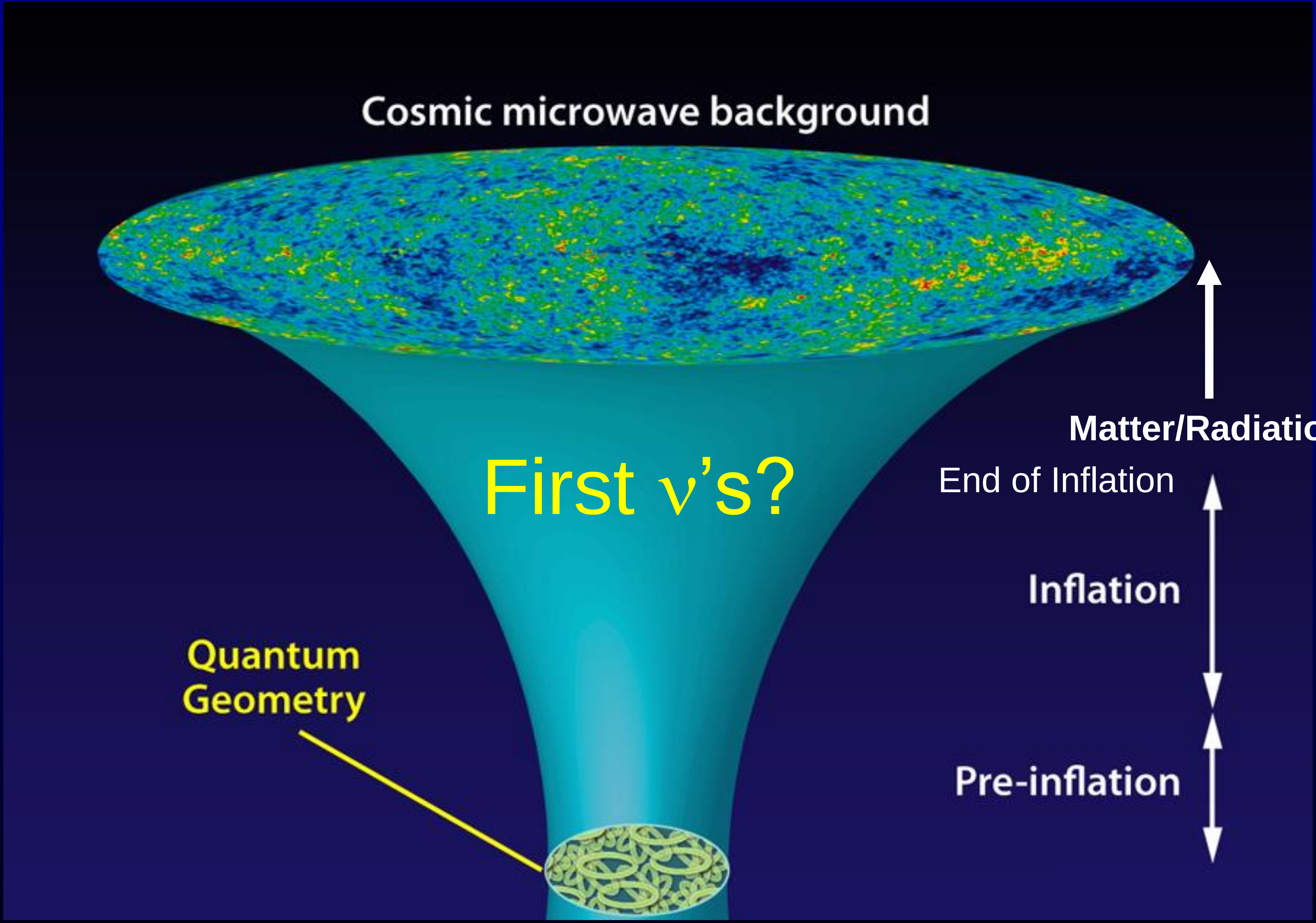
PTOLEMY: Unraveling the Cosmology of Relic Neutrinos

Chris Tully on Behalf of PTOLEMY Collaboration
Princeton University

BiCoQ Research Seminar
MILANO-BICOCCA, MILANO, ITALY
DECEMBER 14, 2023

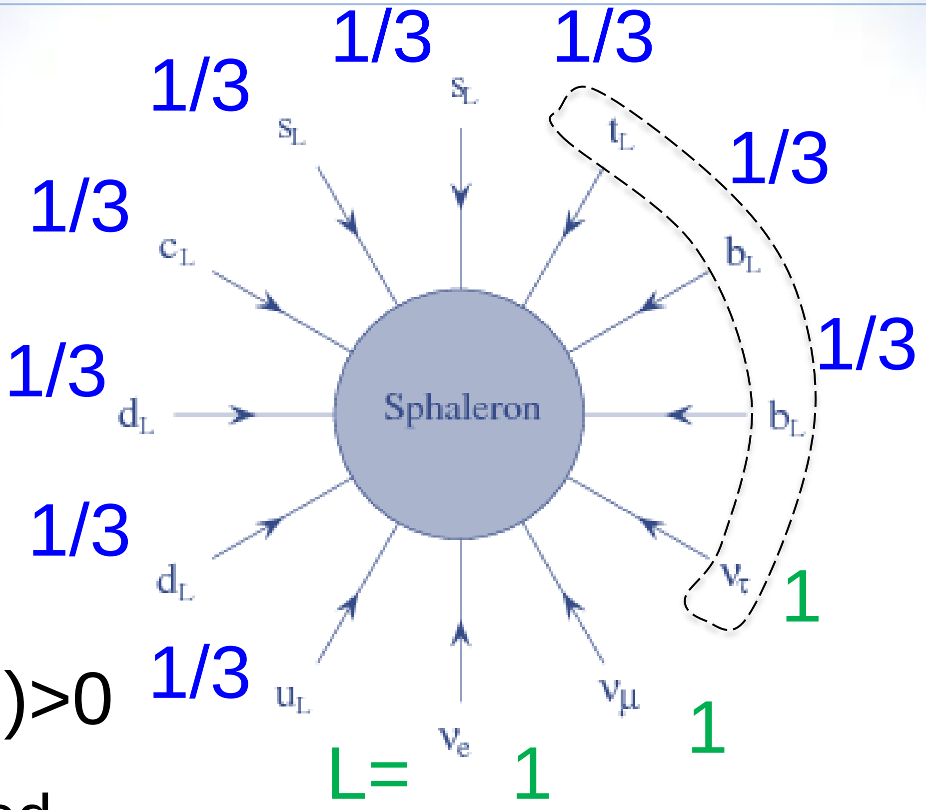
Research supported by
SIMONS FOUNDATION
John Templeton Foundation

Scale-Invariant Power Spectrum



First Neutrinos in the Universe

Sphaleron corresponds to an unstable configuration of fields, which, after a small perturbation, decays to the vacuum by emission of many particles.



Conserved

Δ(B - L)=0

Baryogenesis

Δ(B - anti-B)>0

Balance Drowned in Relic Neutrinos

Δ(L - anti-L)>0

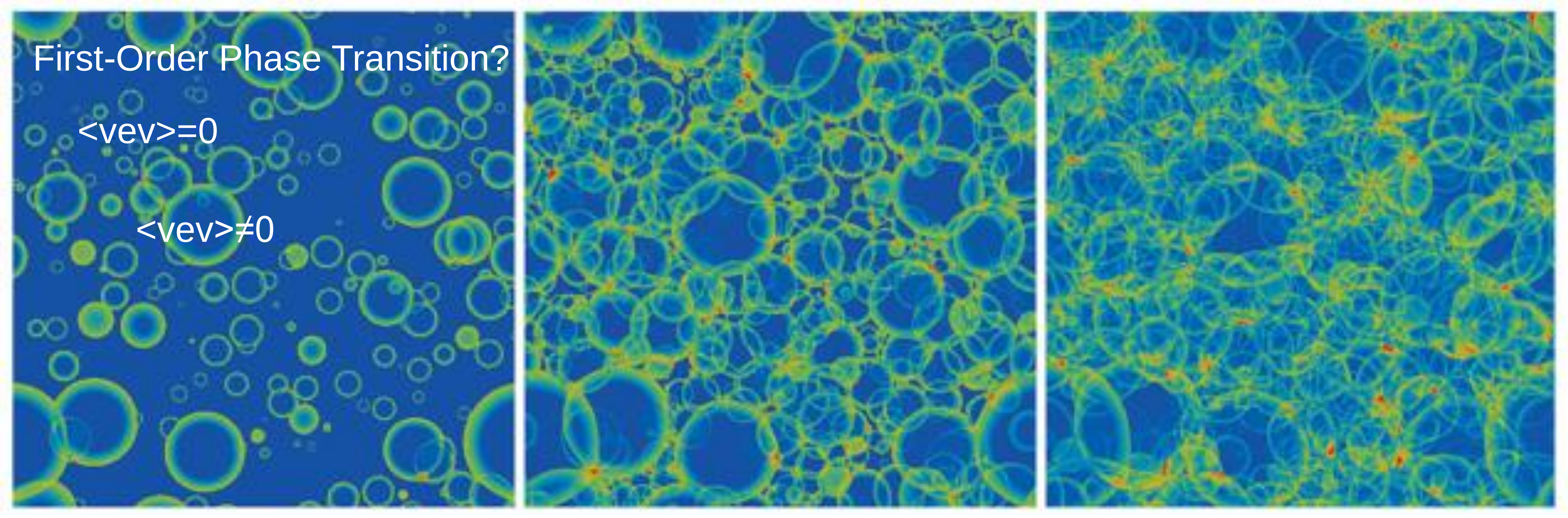
The sphaleron solution is known explicitly and its energy is

$$E \sim \frac{m_W}{\alpha_W} \sim 9\ TeV$$

$$\begin{array}{c} \left(u_L^{2/3} \right) \\ \left(d_L^{-1/3} \right) \\ \left(d_L^{-1/3} \right) \\ + \left(\nu_L \right) \\ \hline = 0 \end{array}$$

Higgs Vacuum Bubbles

Imagine that regions with non-zero <vev> cause Spacetime to grow rapidly overtaking the space with zero <vev>: Like gas bubbles in boiling water

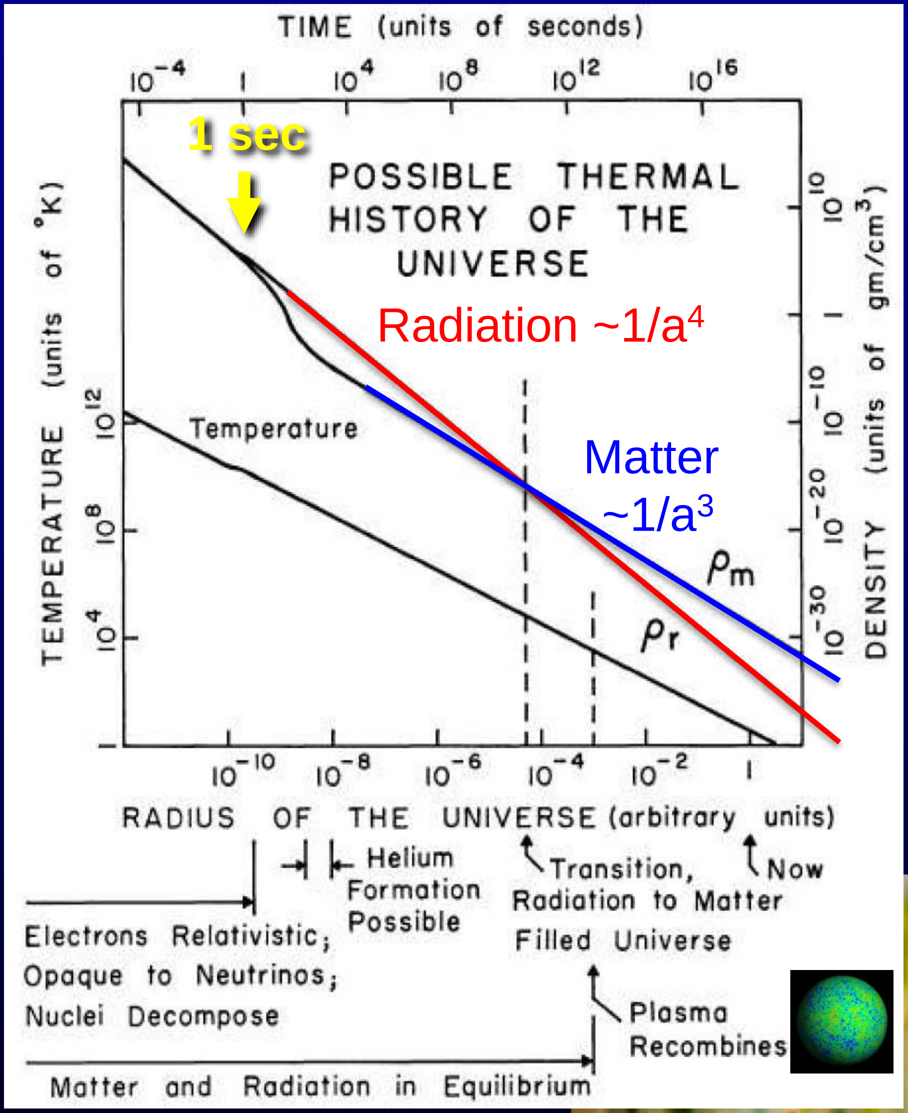


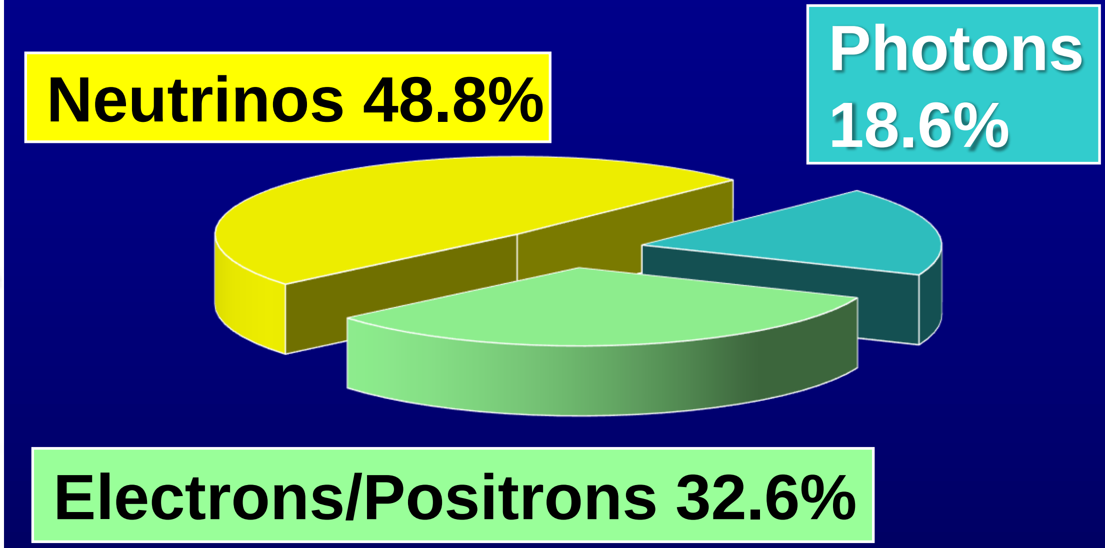
- A ***minimum*** of 3 mass generations needed to have *CP* violating phases in the mass matrices
- Sphaleron process ***not suppressed*** by m_W outside of Higgs vacuum bubbles

https://cerncourier.com/a/electroweak-baryogenesis/

Or Second-Order Phase Transition?

Cosmic Neutrino Background





Neutrinos 48.8%

Photons 18.6%

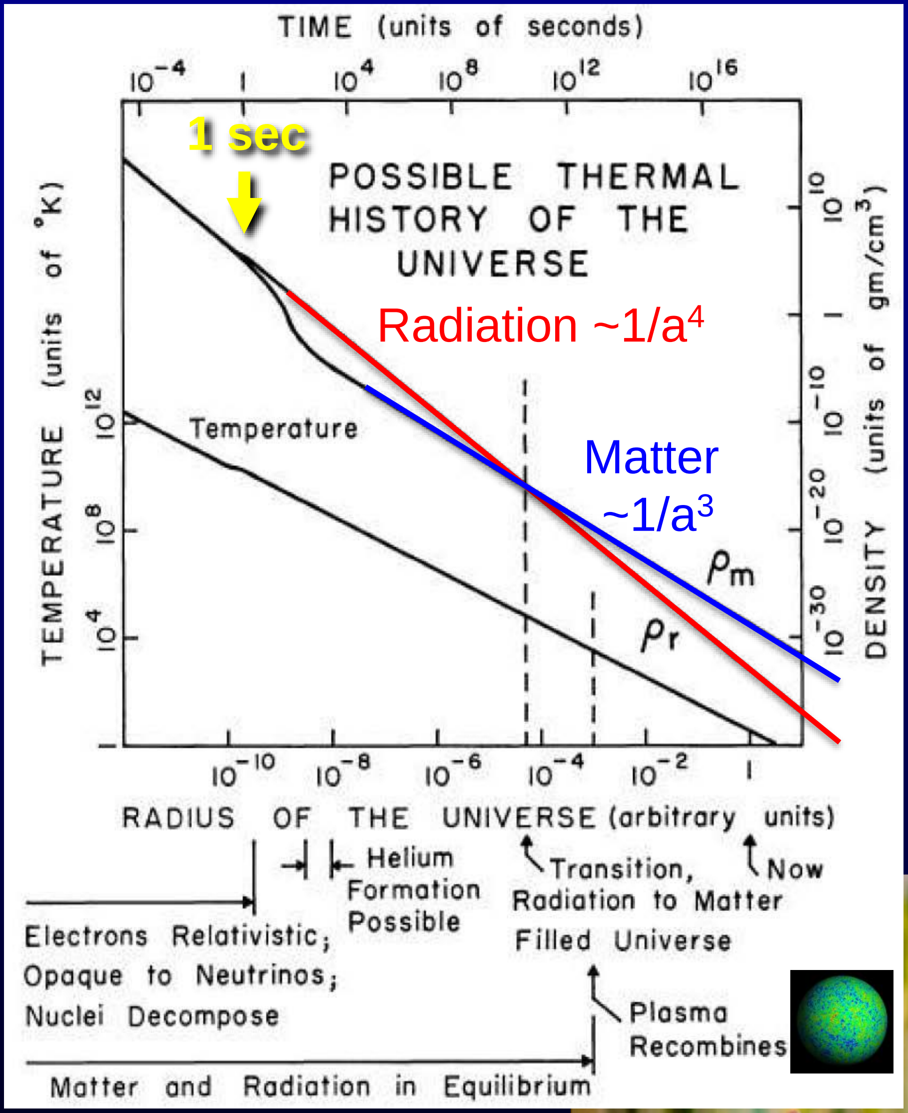
Electrons/Positrons 32.6%

Neutrino Decoupling
(t=1 second)

Dicke, Peebles*, Roll, Wilkinson (**1965**)

Cosmology's Century (2020)

Cosmic Neutrino Background



Number density:

$n_\nu = 112/cm^3$

Temperature:

$T_\nu \sim 1.95K$

Time of decoupling:

$t_\nu \sim 1$ second

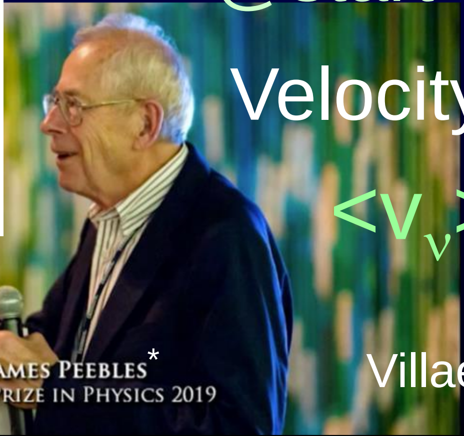
~50% of the Total Energy Density of the Universe

neutron/proton ratio @start of nucleosynthesis

Velocity distribution:

$<v_\nu> \sim T_\nu /m_\nu$

Non-linear distortions
Villaescusa-Navarro et al (2013)



JAMES PEEBLES*
NOBEL PRIZE IN PHYSICS 2019

Dicke, Peebles*, Roll, Wilkinson (**1965**)

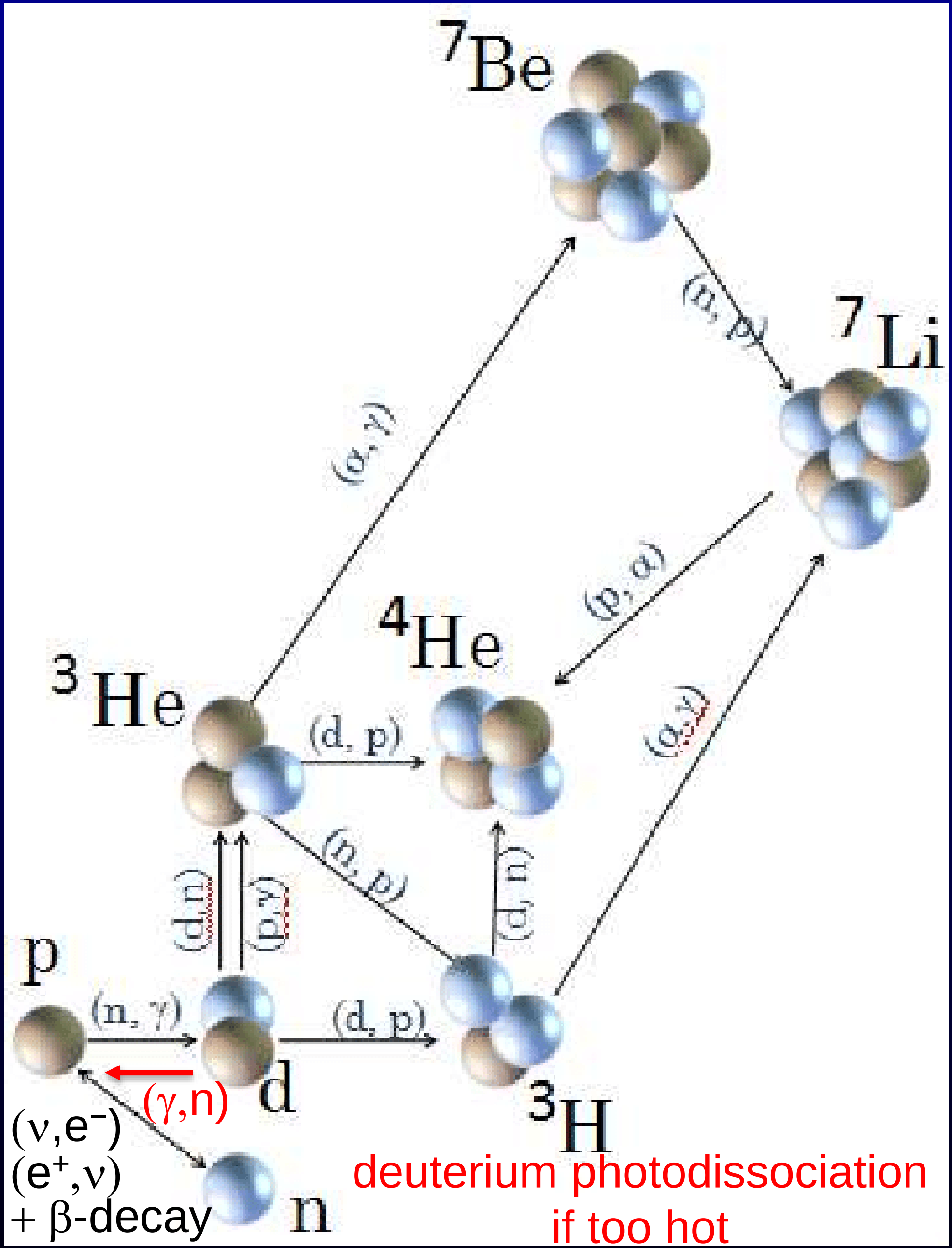
Cosmology's Century (2020)

Our Biggest Fan

December 7, 2023

FRS145: Big Bang Cosmology From the Ground Up

Nucleosynthesis Chain



deuterium photodissociation if too hot

Protons/Neutrons scrambled until the temperature drops below ~0.7 MeV

Neutrons decay with a lifetime of 888 sec

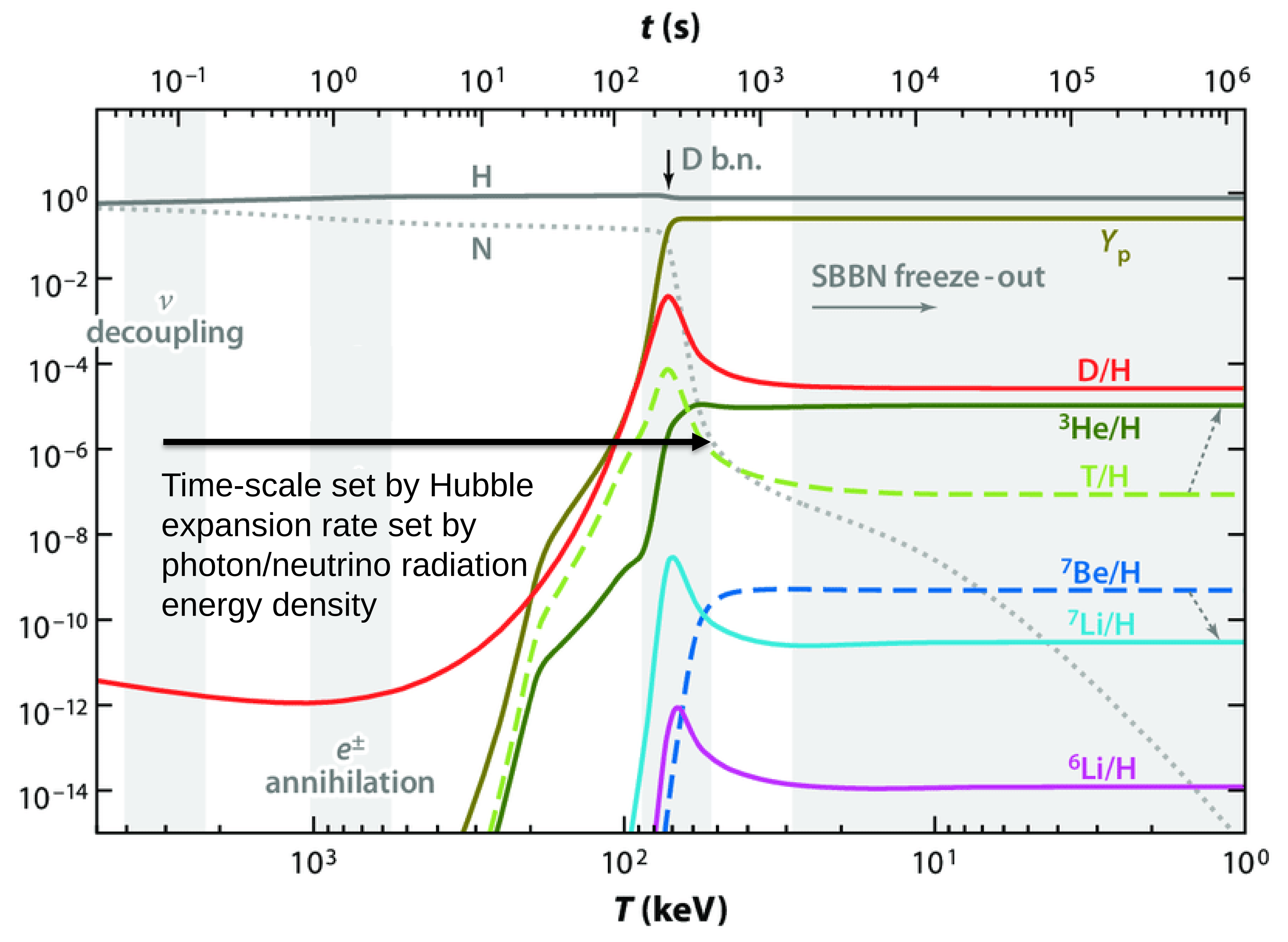
Weak interactions:

$$n \leftrightarrow p + e^- + \bar{\nu}$$
$$\nu + n \leftrightarrow p + e^-$$
$$e^+ + n \leftrightarrow p + \bar{\nu}$$

$$n_\gamma >> n_B$$

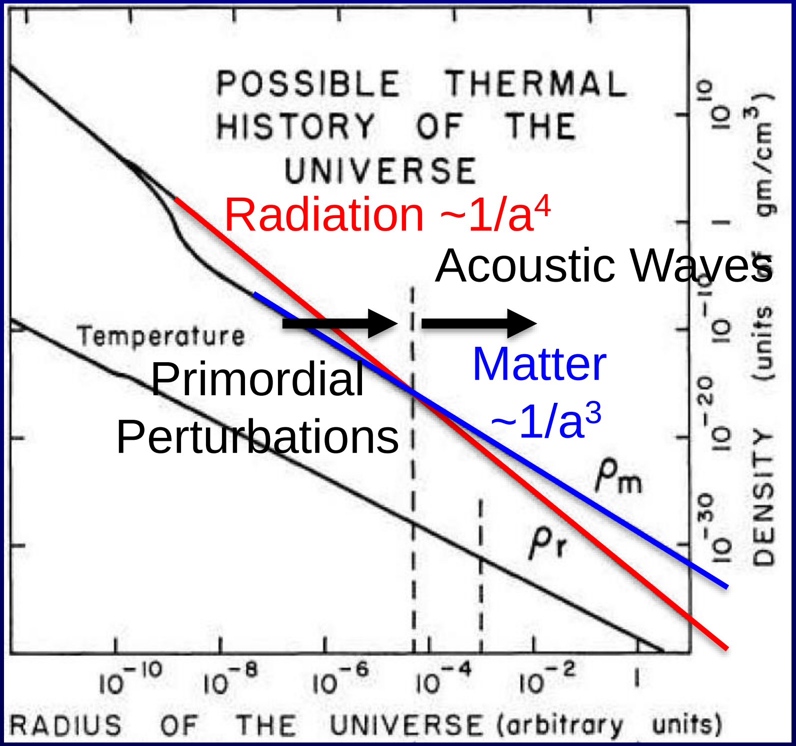
Photodissociation of Deuterium slows down at temperatures below ~0.08 MeV at roughly 120 seconds into BBN

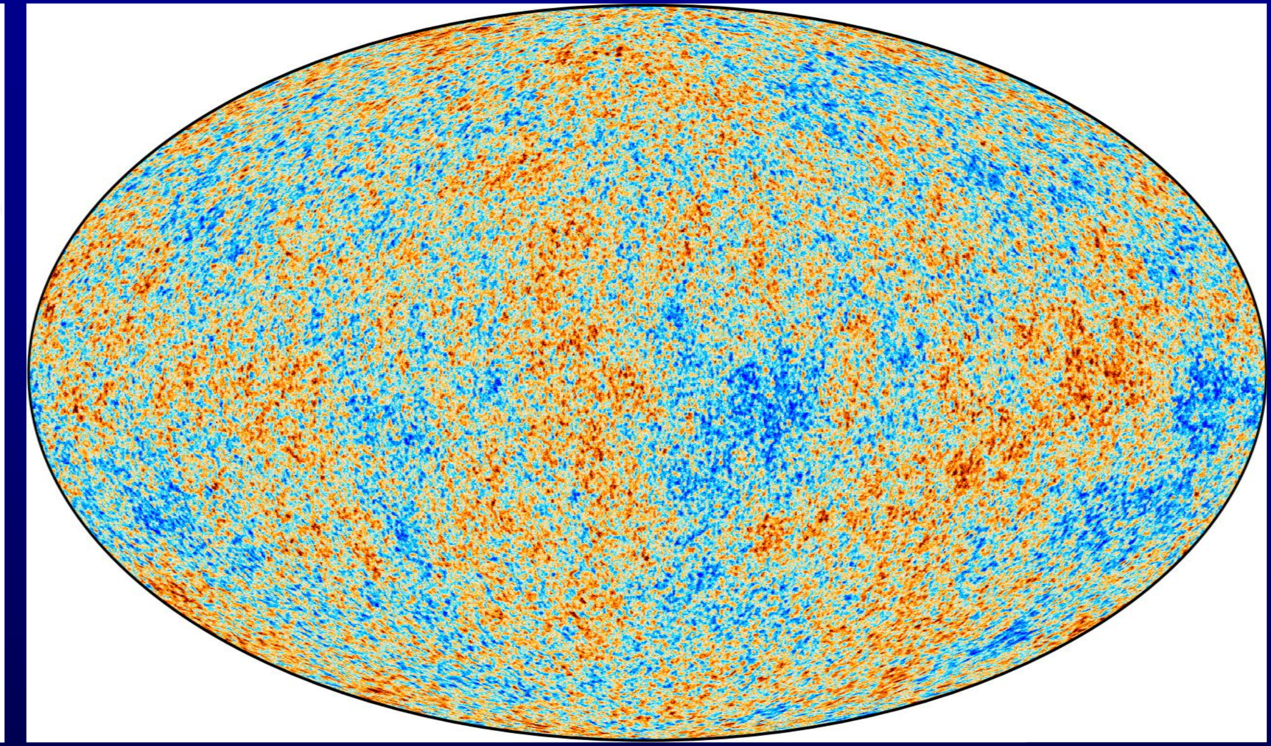
BBN Predictions



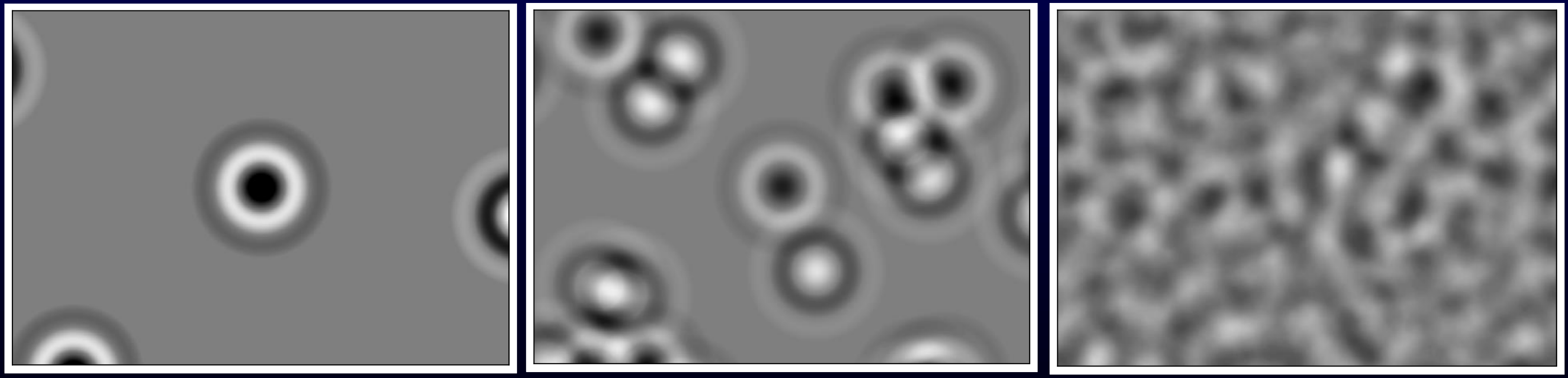
Time-scale set by Hubble expansion rate set by photon/neutrino radiation energy density

Superposition of Sound Waves





https://www.cosmos.esa.int/documents

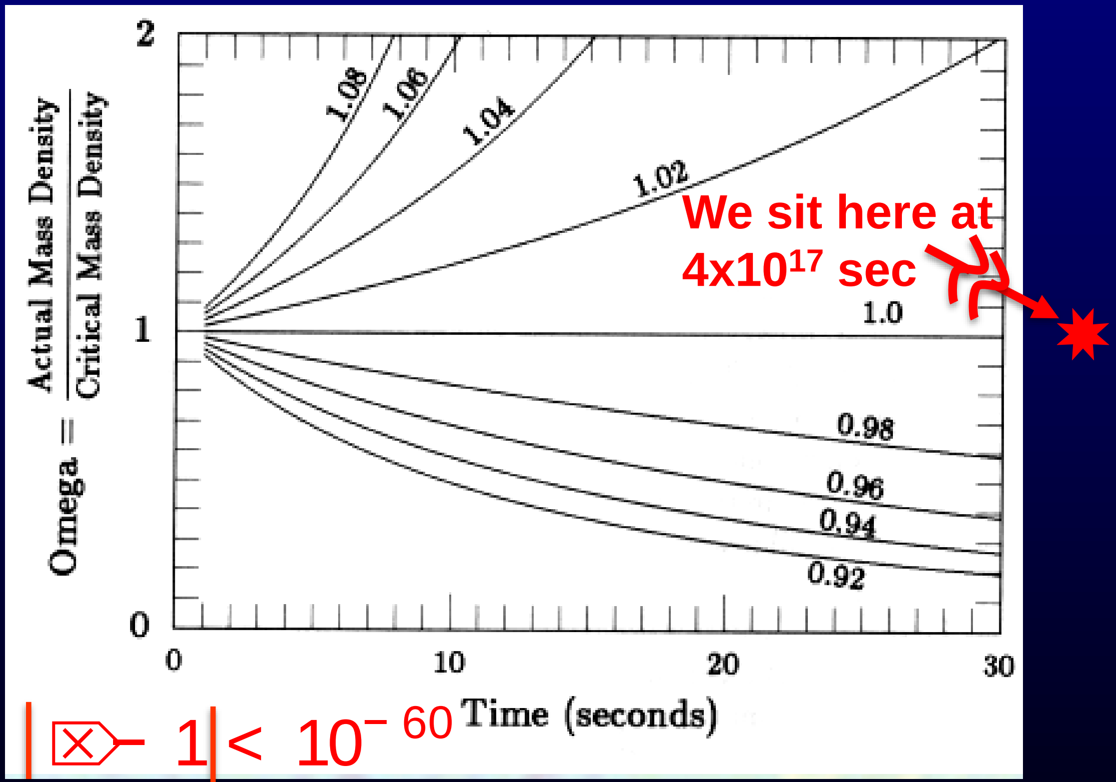


Cosmic Tightrope

We can ask, how close to $\Omega = 1$ did the Universe need to be in order for Spacetime to be flat today?

Answer: The tiny dark energy density (assuming it is a constant) that was completely negligible in the early Universe had to be so accurately accounted for at the end of inflation $\Omega = 1$ that it would be precisely 69% of the total critical density today.

$$\Omega = 1$$



We sit here at 4×10^{17} sec

$|\boxtimes - 1| < 10^{-60}$

Initial condition

Nucleosynthesis:

$$|\Omega - 1| < 10^{-18}$$

Recombination:

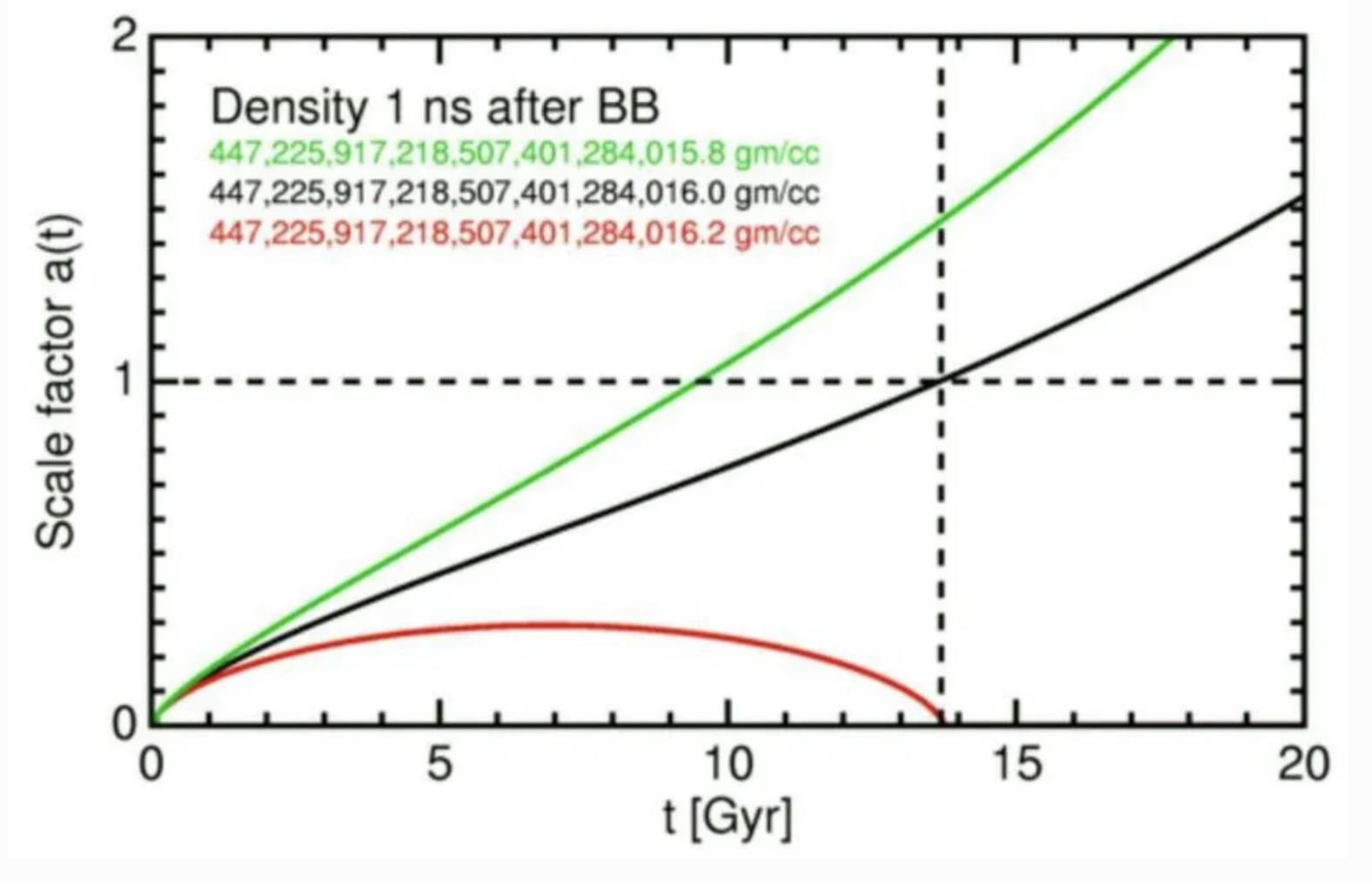
$$|\Omega - 1| < 10^{-5}$$

Today:

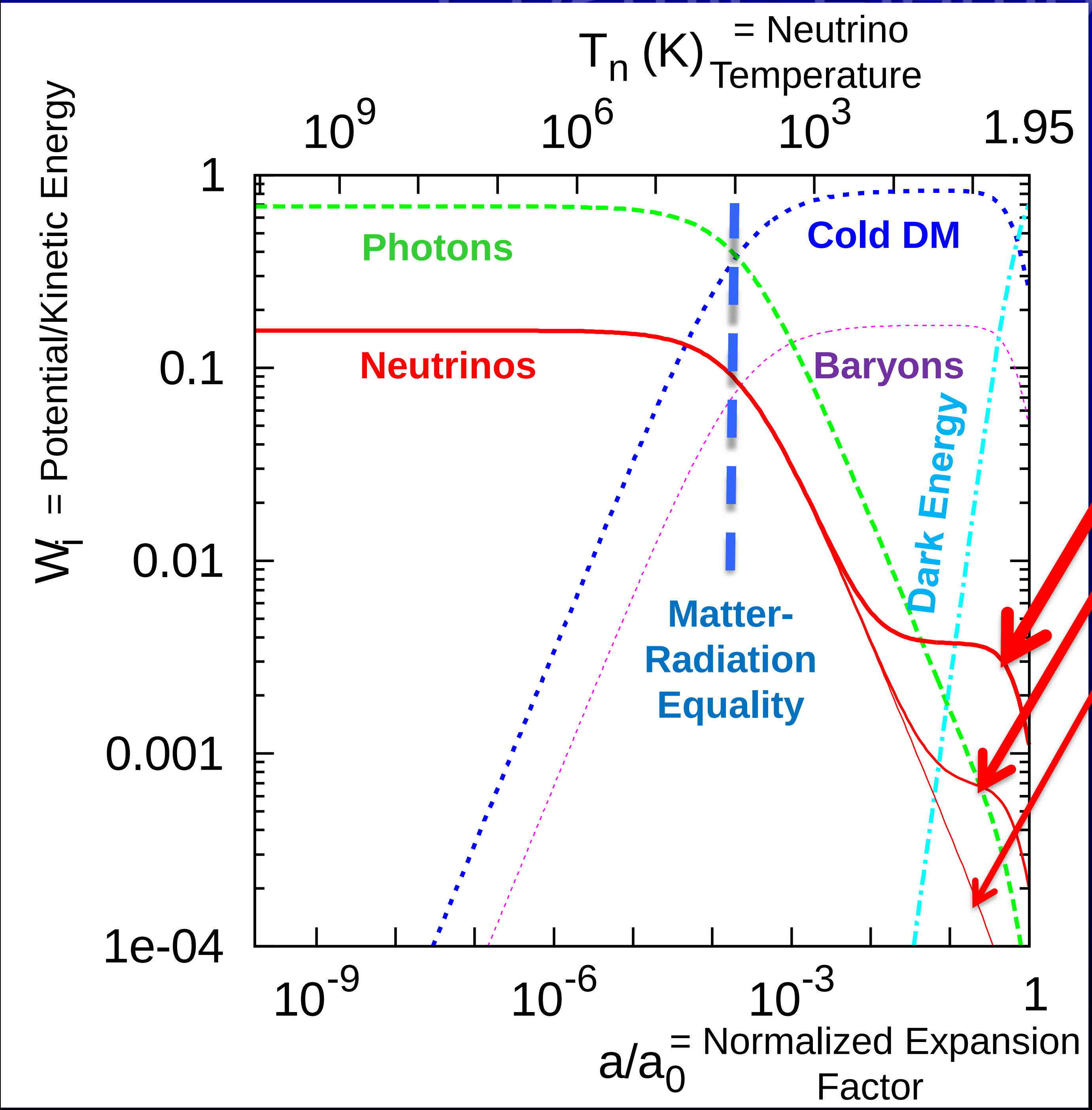
$$|\Omega - 1| < 3 \times 10^{-3}$$

How about the energy density from neutrino mass?

Flatness Problem



Cosmic Elements



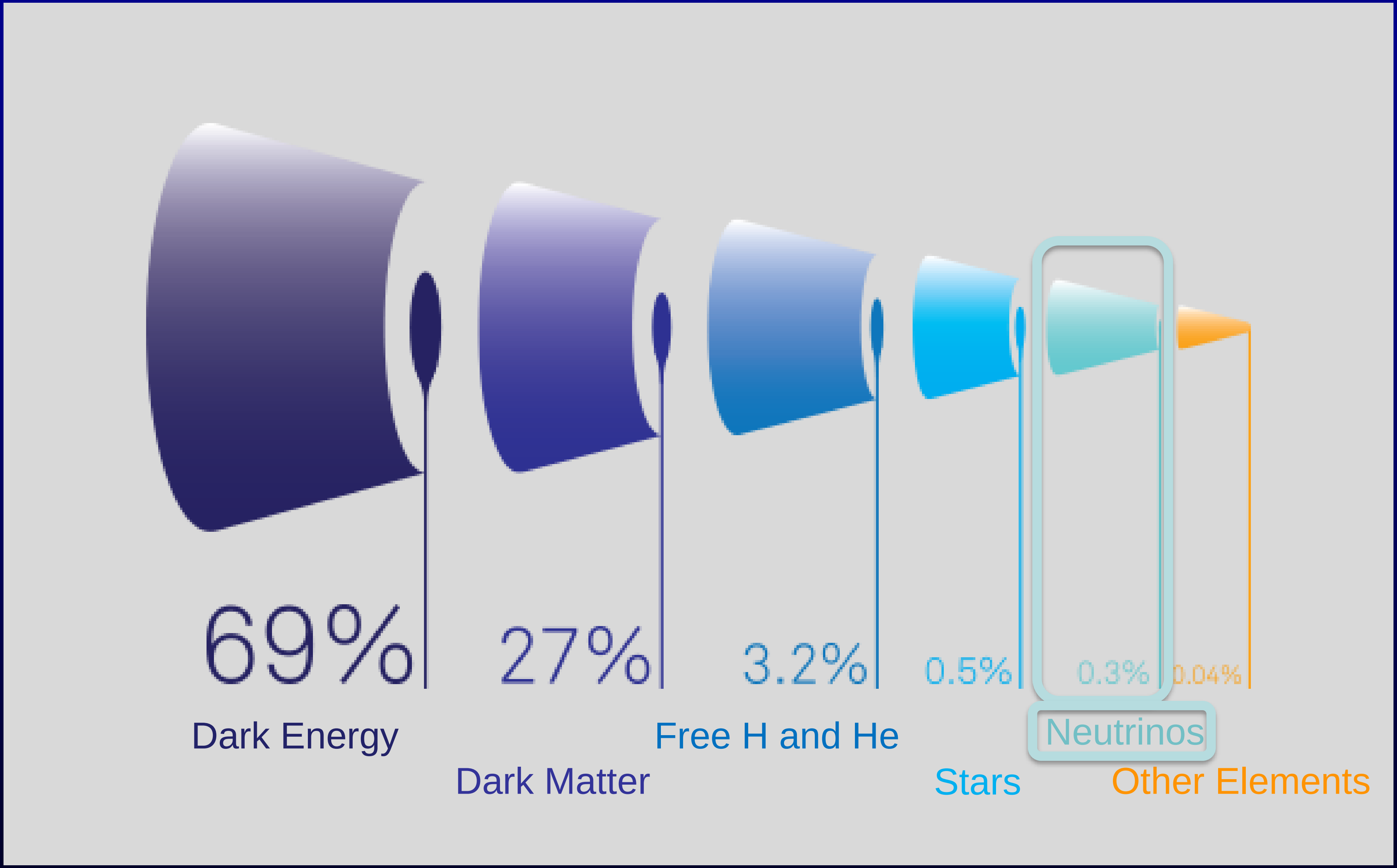
J. Lesgourgues

Individual neutrino contributions assuming Normal Hierarchy and
$m_3 = 0.05$ eV,
$m_2 = 0.009$ eV,
$m_1 = 0$

At least 1% Ω_{baryon}

Saved by the bell?

Present Universe Ω=1

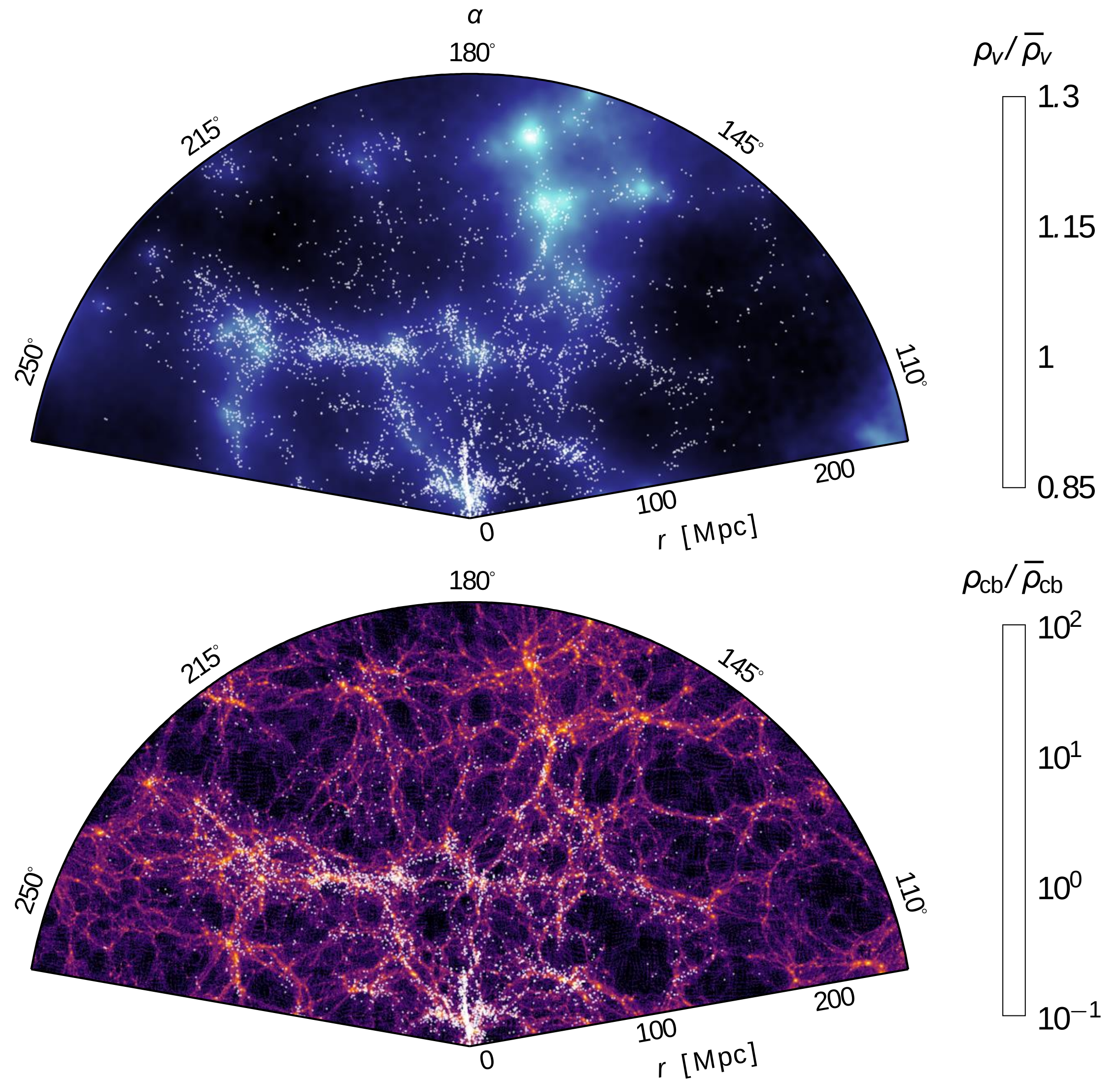


Neutrino Sky Modeling

Fabian Zimmer, Camila A. Correa, Shin'ichiro Ando

Influence of local structure on relic neutrino abundances and anisotropies

https://arxiv.org/abs/2306.16444

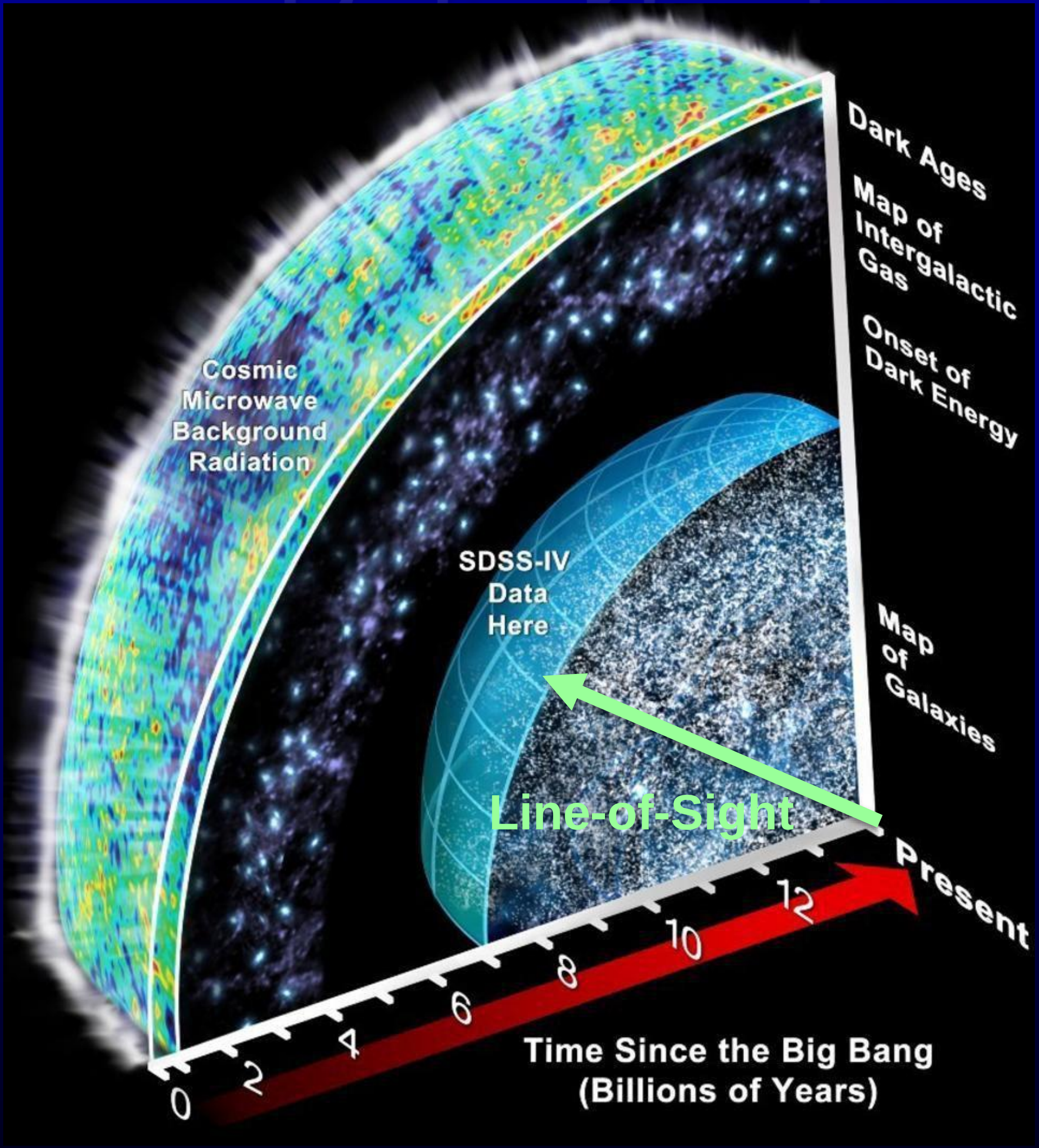


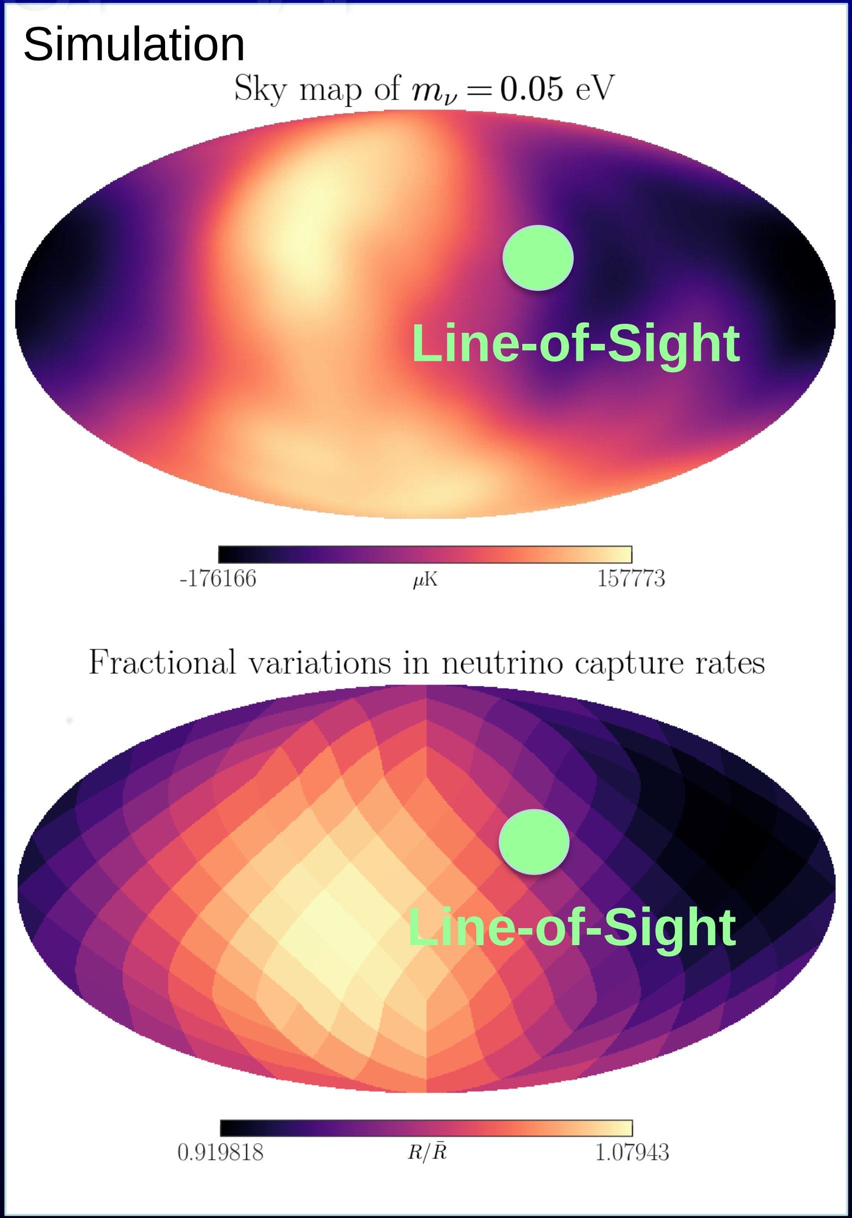
Willem Elbers, Carlos S. Frenk, Adrian Jenkins, Baojiu Li, Silvia Pascoli, Jens Jasche, Guilhem Lavaux, Volker Springel

Where shadows lie: reconstruction of anisotropies in the neutrino sky

https://arxiv.org/abs/2307.03191

Relic Neutrino Sky Map

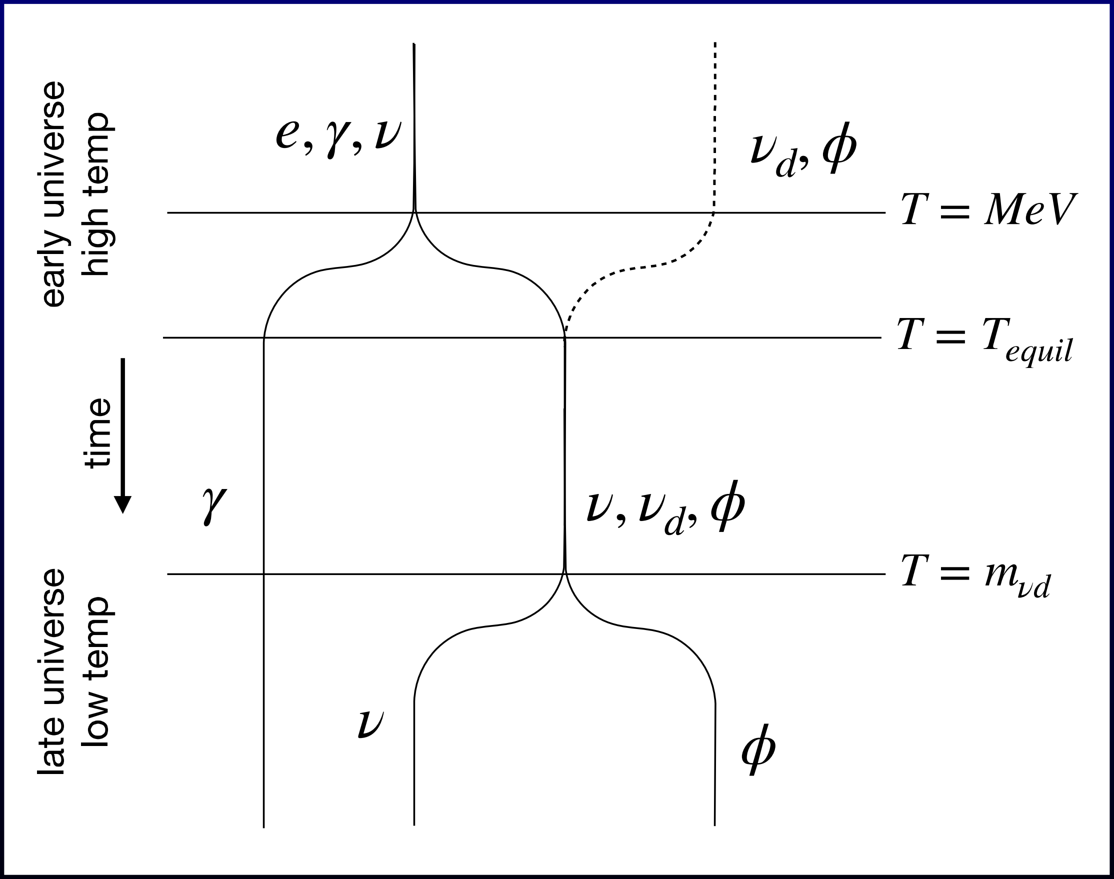




Tully, Zhang, http://arxiv.org/abs/2103.01274 First citation came from Jim Peebles
https://iopscience.iop.org/article/10.1088/1475-7516/2021/06/053
“Multi-Messenger Astrophysics with the Cosmic Neutrino Background”, JCAP 06 (2021) 053

Non-Standard Thermal History: Re-thermalization of Neutrinos in the ΛCDM Desert

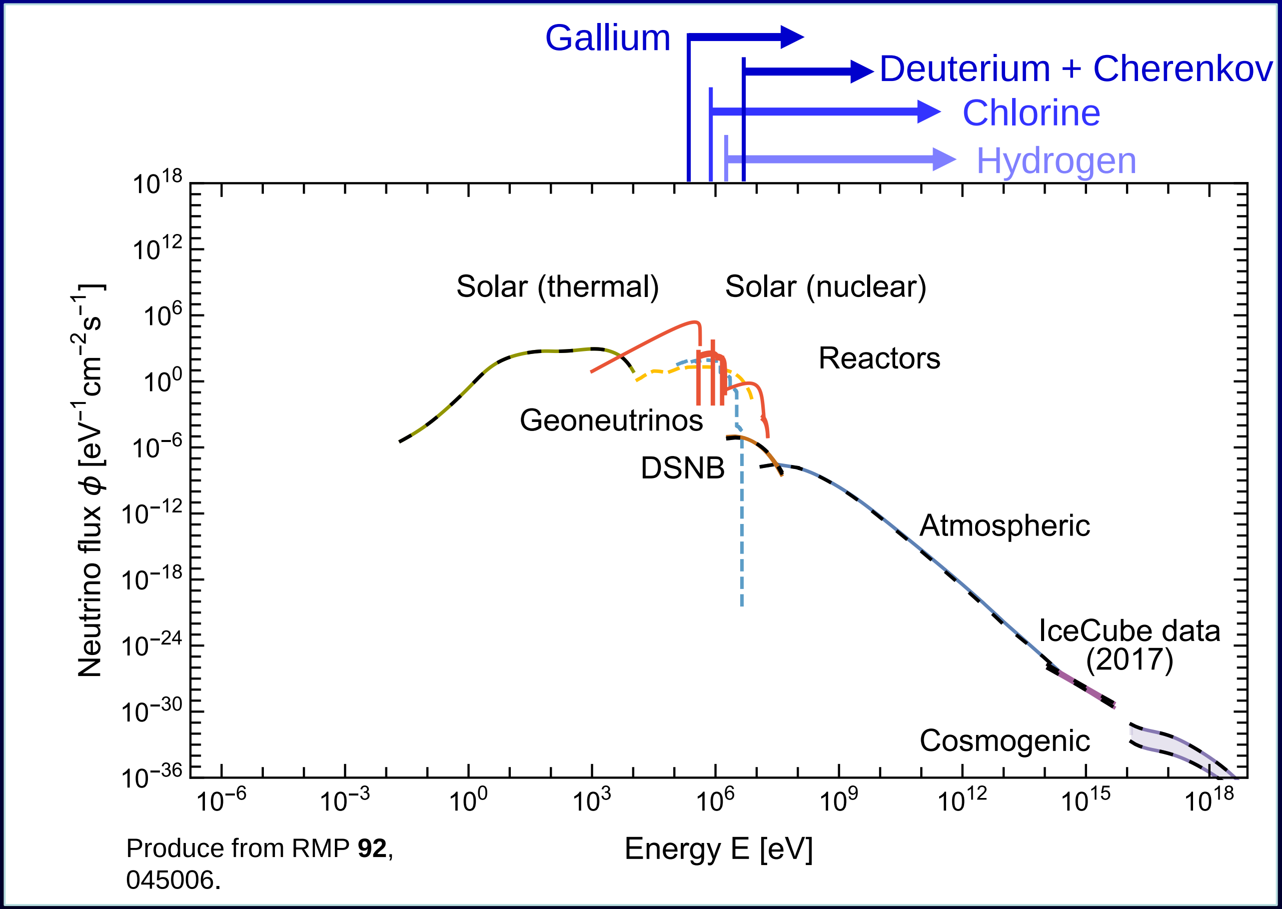
Daniel Aloni, Melissa Joseph, Martin Schmaltz, Neal Weiner
Dark Radiation from Neutrino Mixing after Big Bang Nucleosynthesis
https://arxiv.org/abs/2301.10792



What if the post-BBN history of relic neutrinos are not as we expect and neutrinos have a non-trivial influence on the dark sector?

This would change how many we would detect today.

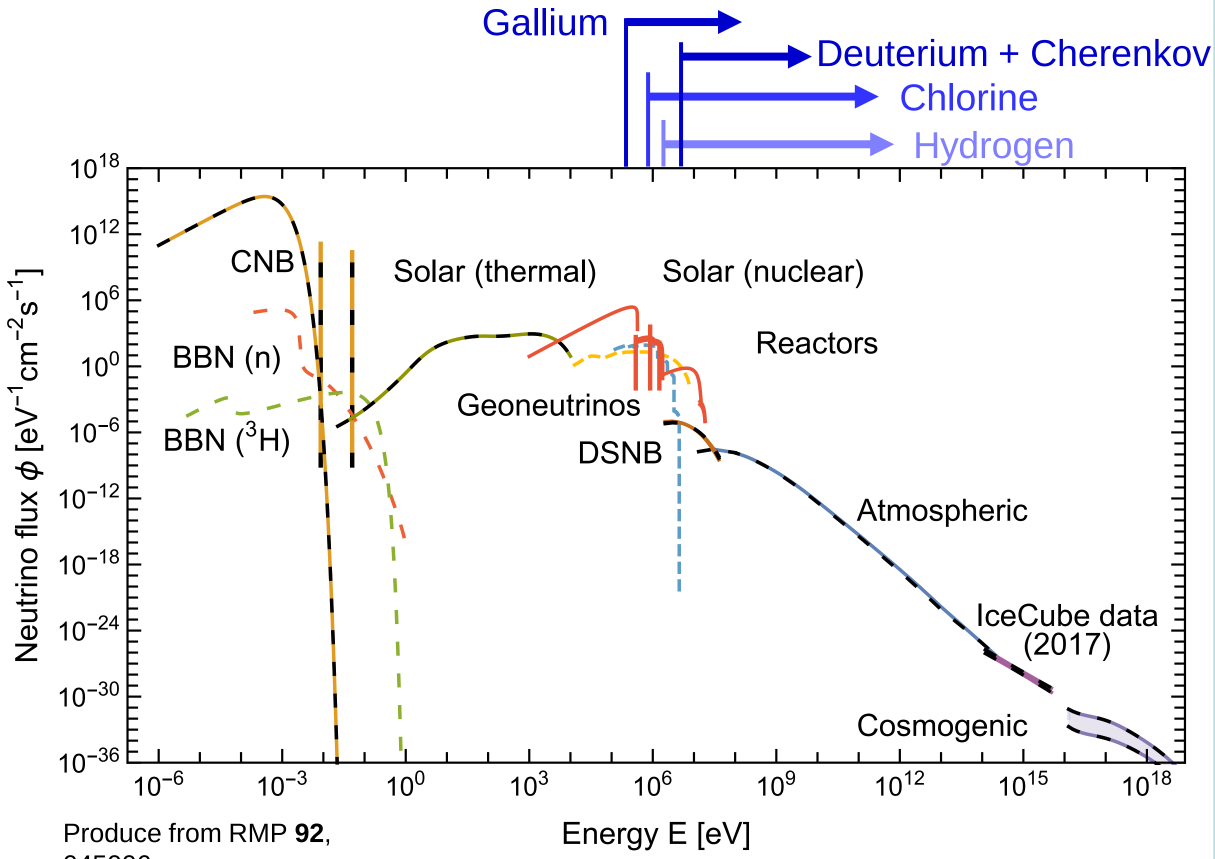
Cosmic Neutrino Background



Produce from RMP **92**, 045006.

- Neutrinos have been measured for more than 60 years.
- Previous methods have energy thresholds in ~MeV for charged and neutral current scattering or capture on Gallium, Chlorine, etc.

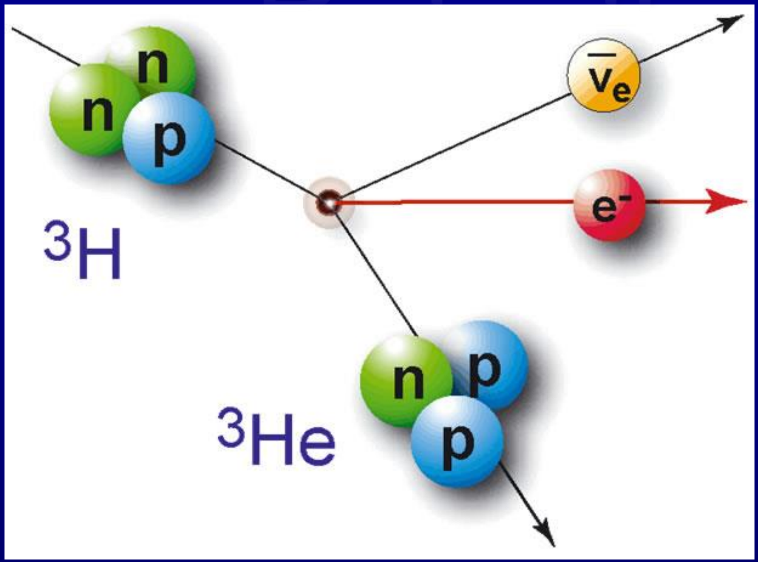
Cosmic Neutrino Background



Produce from RMP **92**, 045006.

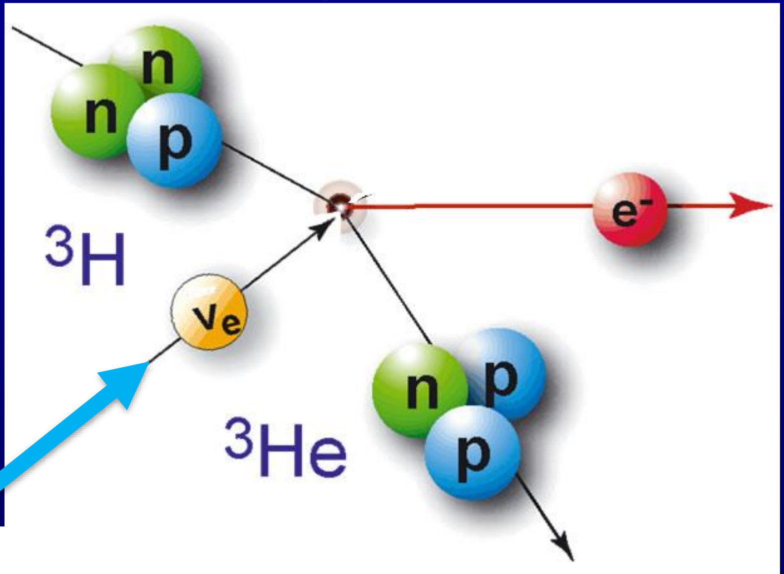
- The CNB is shown for a minimal mass spectrum here for 0, 8.6, and 50 meV, producing a blackbody spectrum plus two monochromatic lines for nonrelativistic neutrinos with energies corresponding to their masses.
- Detection requires a reaction with no threshold.

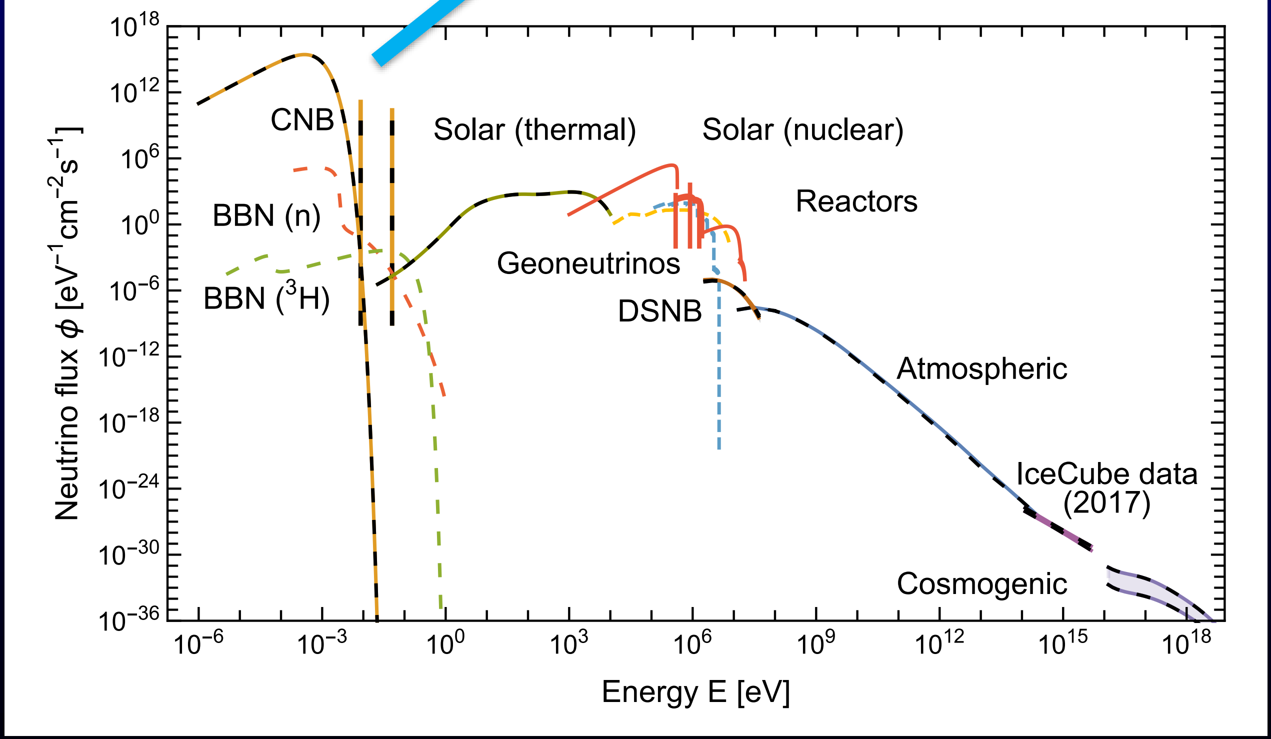
Detecting sub-eV Neutrinos



Tritium β-decay
(12.3 yr half-life)

Neutrino capture on Tritium

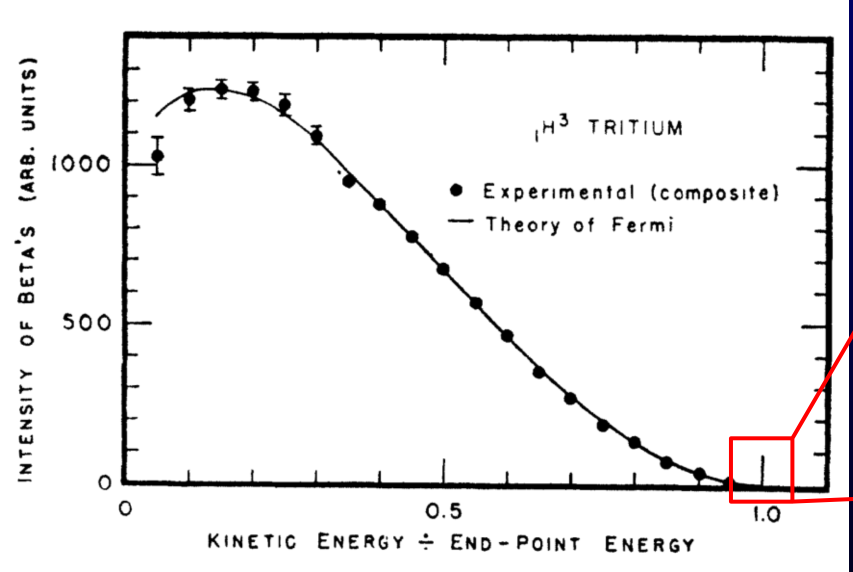




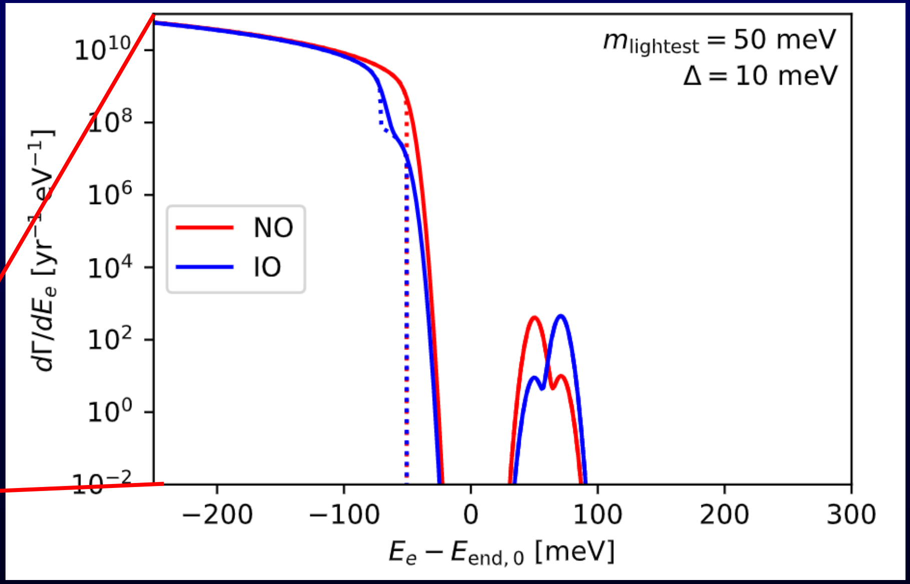
Detecting CNB Using Capture on Tritium

- Steven Weinberg laid out basic concepts for CNB detection in 1962
- Cocco, Mangano, Messina applied to massive neutrinos in 2007

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_{e} \qquad\qquad {}^{3}\mathrm{H} + \nu_{e} \rightarrow {}^{3}\mathrm{He} + e^{-}$$



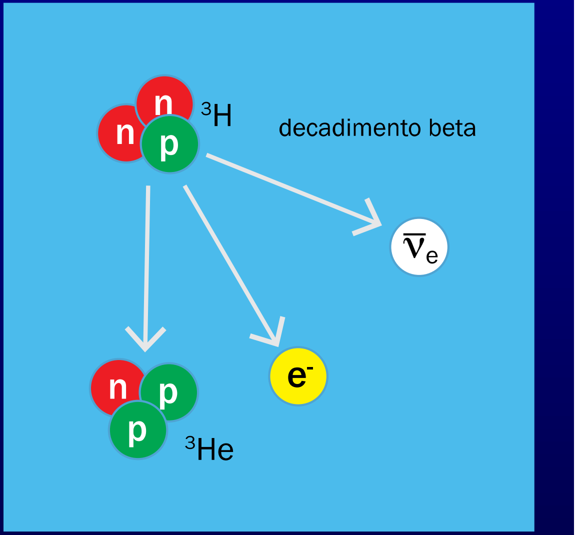
Phys Rev **77**, 402–403 (1950).

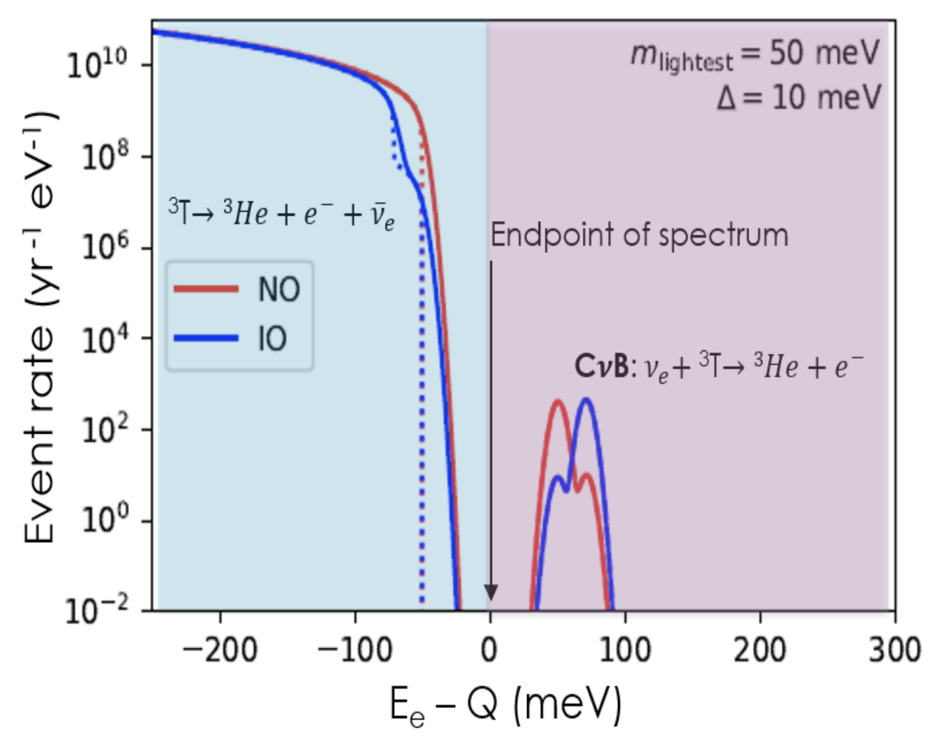


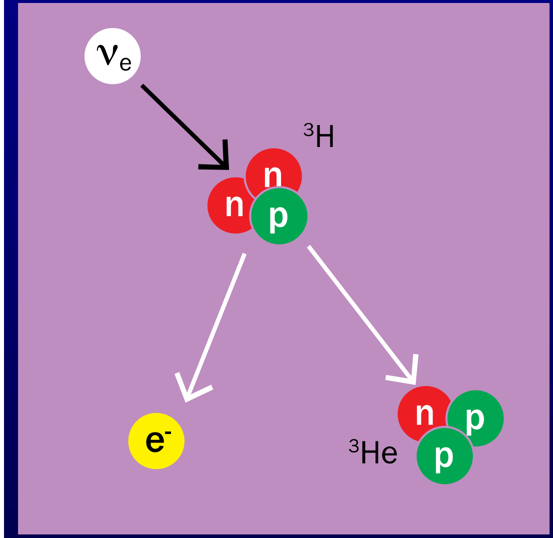
JCAP **2019**, 047–047 (2019).

Detection Concept: Neutrino Capture

Idea for relic neutrino detection originated in a paper by Steven Weinberg in **1962** [*Phys. Rev*. 128:3, 1457] applied for the first time to massive neutrinos in **2007** by Cocco, Mangano, Messina [DOI: 10.1088/1475-7516/2007/06/015]







What do we know?

Electron flavor expected with

m > ~50meV

from **neutrino oscillations**

Gap (2m) constrained to

m < ~200meV

from **precision cosmology**

CνB Detection Requires:

few x 10^{-6} energy resolution set by m_ν

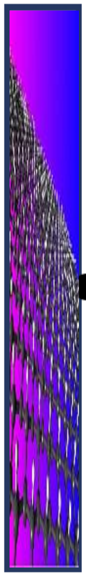
KATRIN ~ 10^{-4} (current limitation)

PTOLEMY: 10^{-4} x 10^{-2}

(compact filter) x (microcalorimeter)

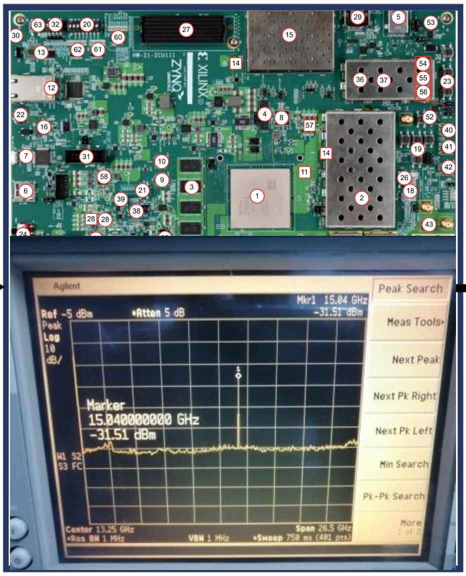
PTOLEMY Conceptual Block Diagram

Target: Relic Neutrino Capture → **RF Tracker: Electron Pre-Measurement** → **Dynamic Filter: Selects endpoint electron in narrow 10^{-4} energy window** → **Micro-calorimeter: Measures few eV electron to 10^{-2} energy resolution**



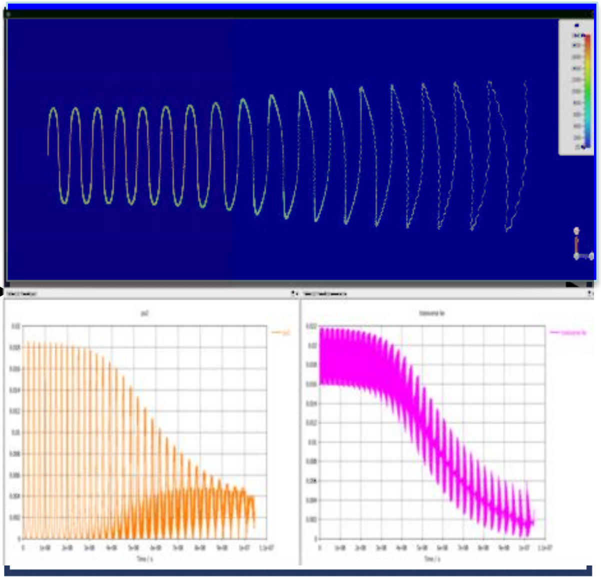
Graphene

monoatomic T storage



RF antenna

measure of K and $K_\perp$

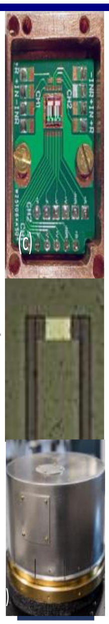


Dynamic EM Filter

particle selector

K_L

is reduced around few eV

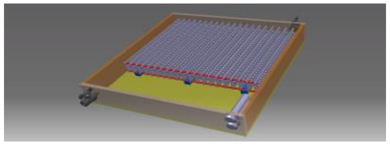


Calorimeters

TES provide a differential E measurement

HV

18.6kV

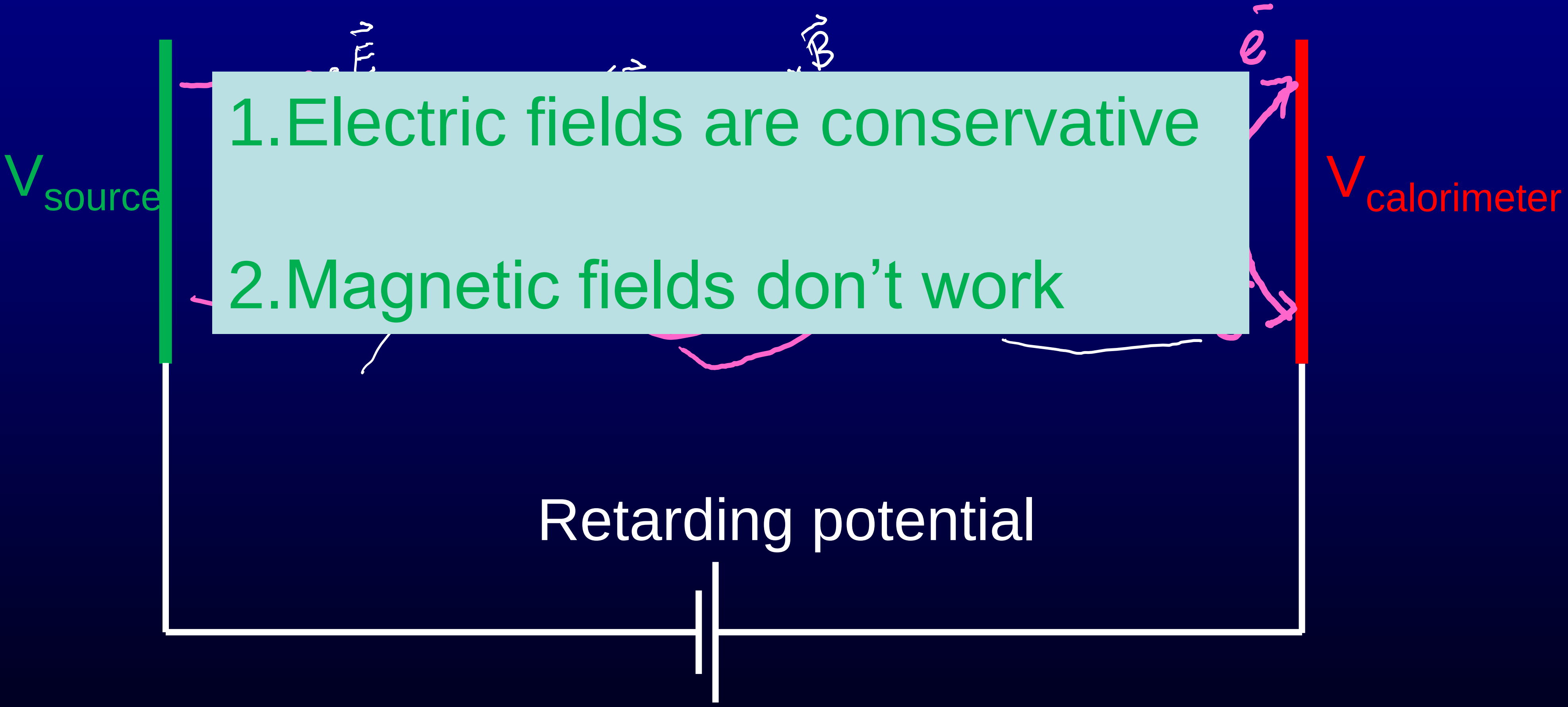


$$E_{Total} = q\left(V_{TES} - V_{Target}\right) + E_{RFcorr} + E_{cal}$$

https://ptolemy.lngs.infn.it

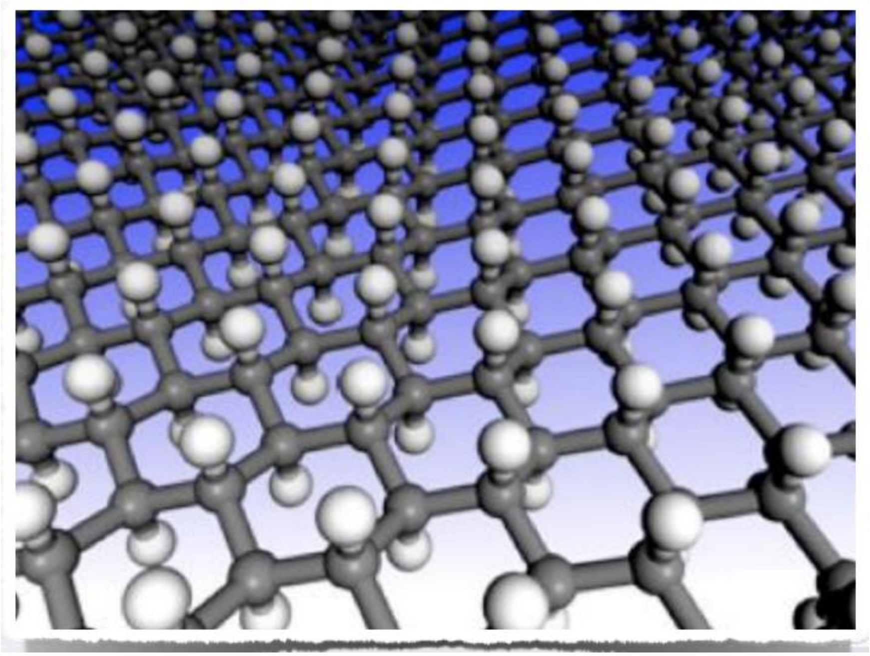
PTOLEMY Conceptual Block Diagram

Target: Relic Neutrino Capture → **Micro-calorimeter: Measures few eV electron to 10^{-2} energy resolution**



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

Tritium-loaded Graphene



>90% Loading Achieved (using ^{1}H)
World Record effort led by PTOLEMY researchers

Mahmoud Mohamed Saad Abdelnabi et al 2021 Nanotechnology 32 035707

Mahmoud Mohamed Saad Abdelnabi et al Nanomaterials 2021, 11(1), 130

Parma, Italy
Now at La Sapienza

Tritium Laboratory Karlsruhe (TLK) recently demonstrated tritium-loading on Graphene

https://arxiv.org/abs/2310.16645

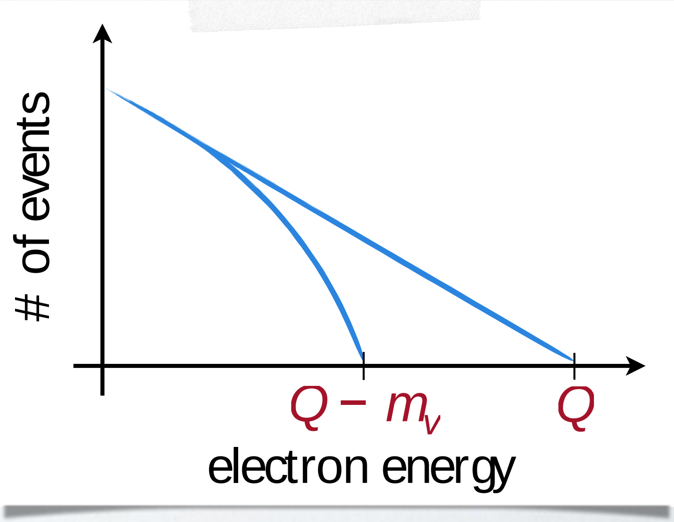
NEUTRINO MASS

$$n \rightarrow p + e^- + \bar{\nu}_e$$

The electron spectrum depends parametrically on the neutrino mass:

$$\frac{dN_\beta}{dK_e} \equiv f(K_e; m_\nu)$$

The effect is much stronger near the end-point



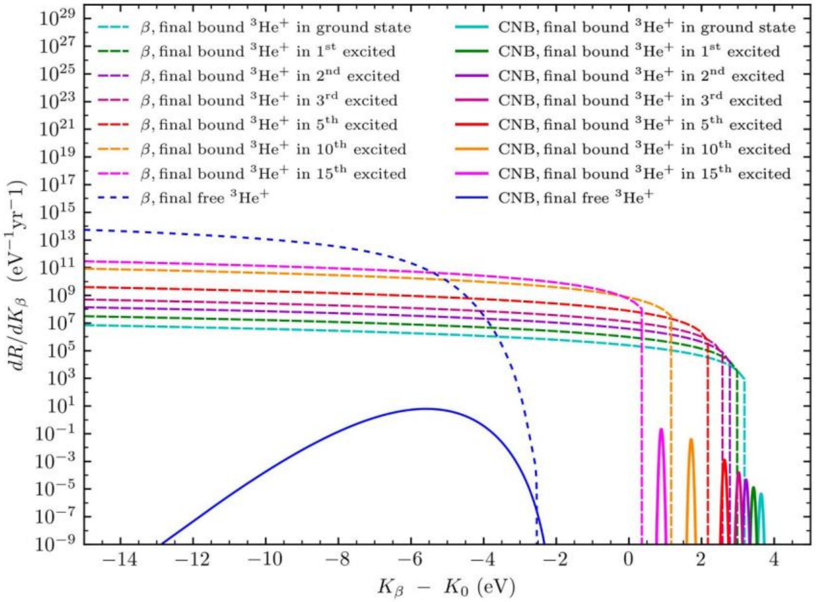
Measure the near end-point spectrum

↓

Fit the neutrino mass

Tritium-loaded Graphene Endpoint Spectra

- sensitivity estimate for “bare” Tritium spectrum (i.e. in vacuum decay)
- effect on sensitivity of Heisenberg ZPF in the initial state for free $^3He^+$ decay
- **TODO**: sensitivity from analysis of end-points of bound $^3He^+$ decays

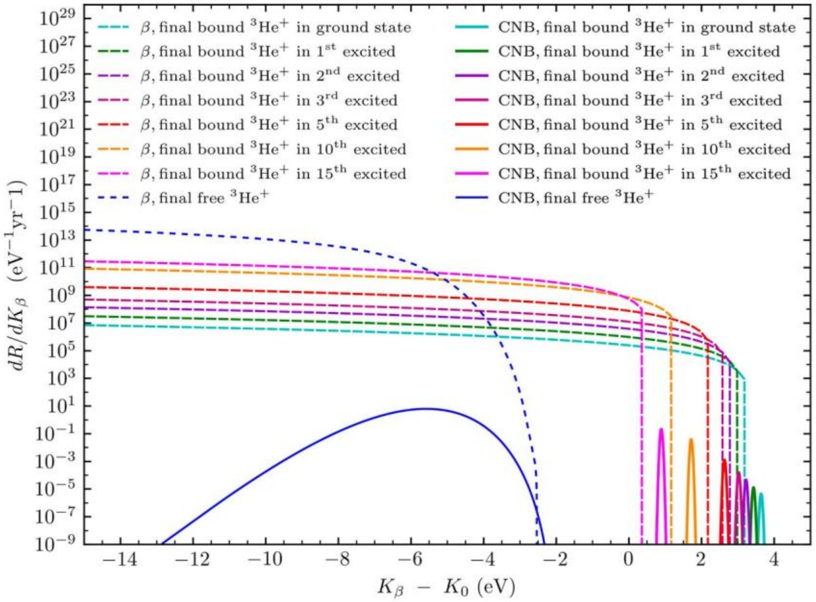


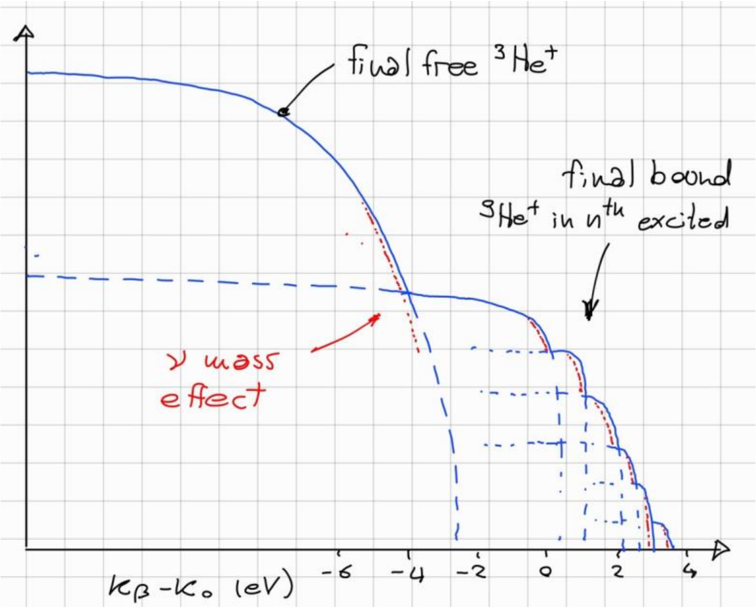
A. Esposito/A.Casale

Multi-endpoints from 3D Harmonic Oscillator Excitations of 3He+ bound on Graphene

Potential New Paradigm to Neutrino Mass Measurement

- sensitivity estimate for “bare” Tritium spectrum (i.e. in vacuum decay)
- effect on sensitivity of Heisenberg ZPF in the initial state for free $^3He^+$ decay
- **TODO**: sensitivity from analysis of end-points of bound $^3He^+$ decays



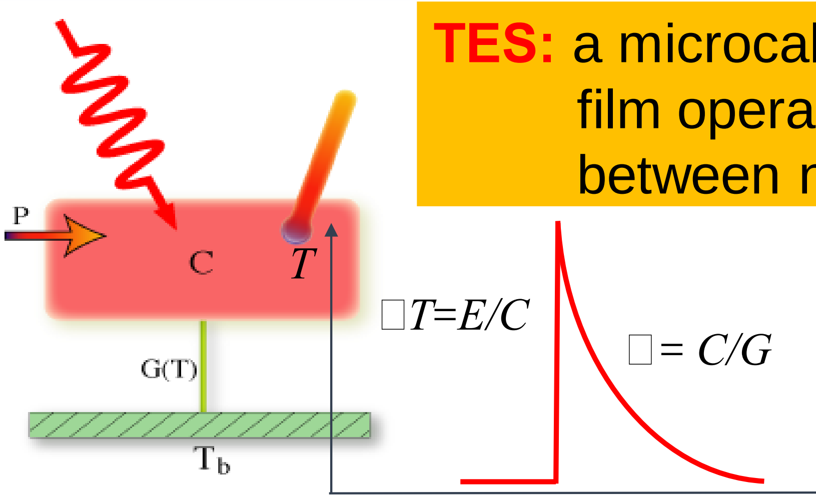


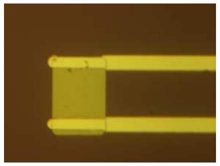
A. Esposito/A.Casale

A. Nucciotti

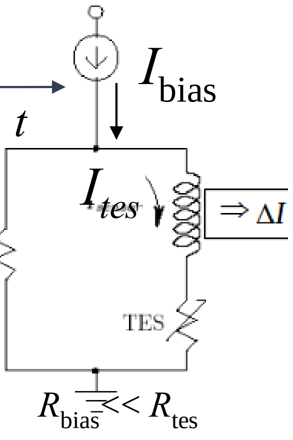
Newly Fabricated TES Micro-Calorimeters

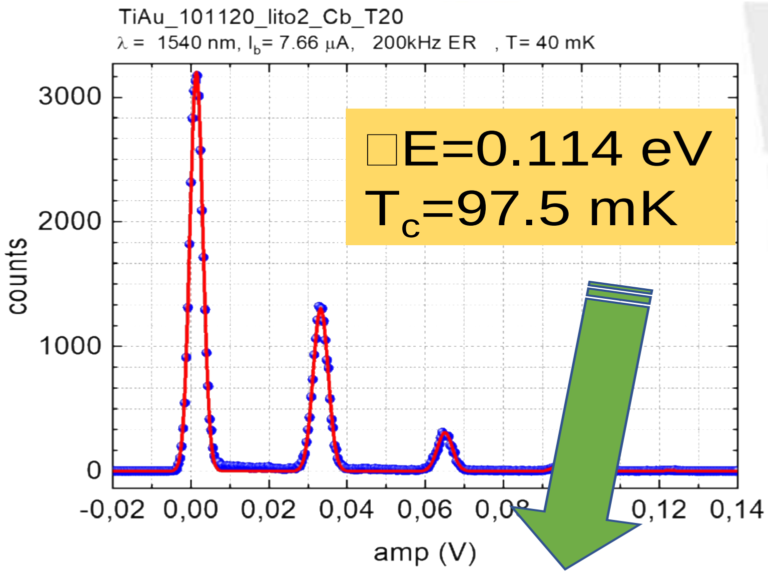
TES: a microcalorimeter made by a superconducting film operated in the temperature region between normal and superconducting state



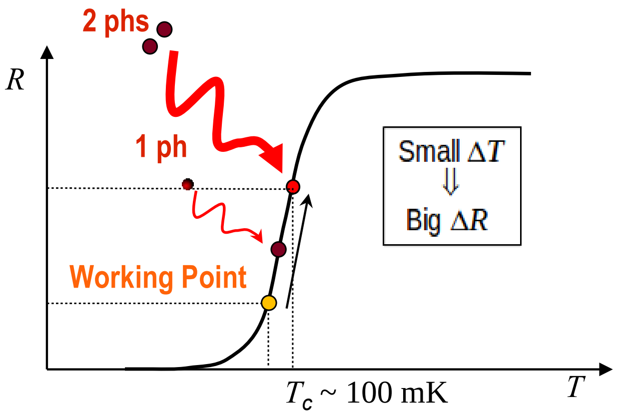


20 µm X 20 µm





ΔE=0.114 eV
T_c=97.5 mK



ΔT ⇨ ΔR @ Voltage bias

Best Resolution with

4 times greater area

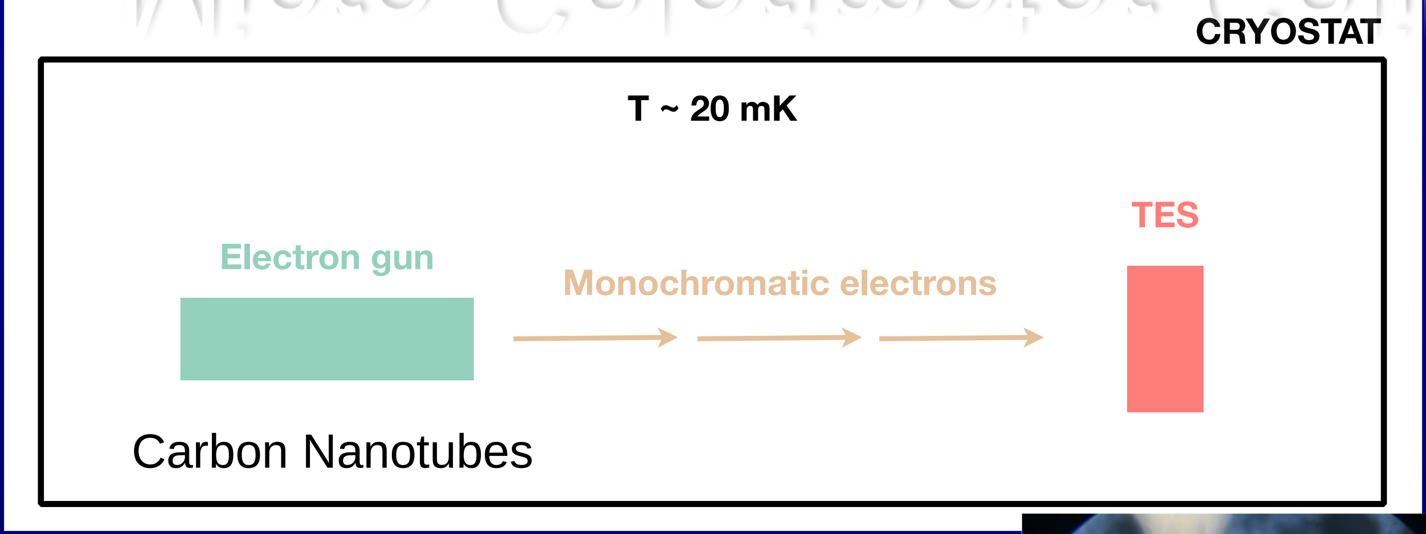
Photon Number Reso

M. Rajteri

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Micro-calorimeter performs well (σ_E~50meV) on IR photons

Micro-Calorimeter Calibration



CRYOSTAT

T ~ 20 mK

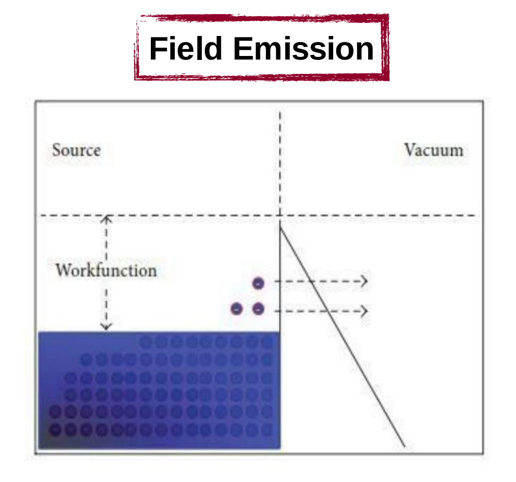
Electron gun

Monochromatic electrons

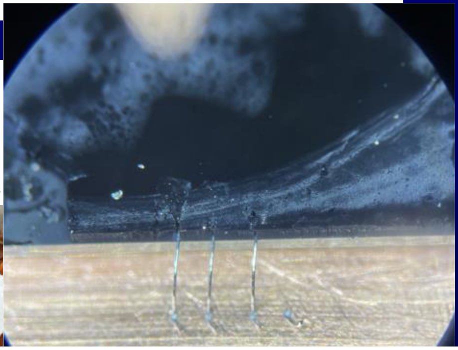
TES

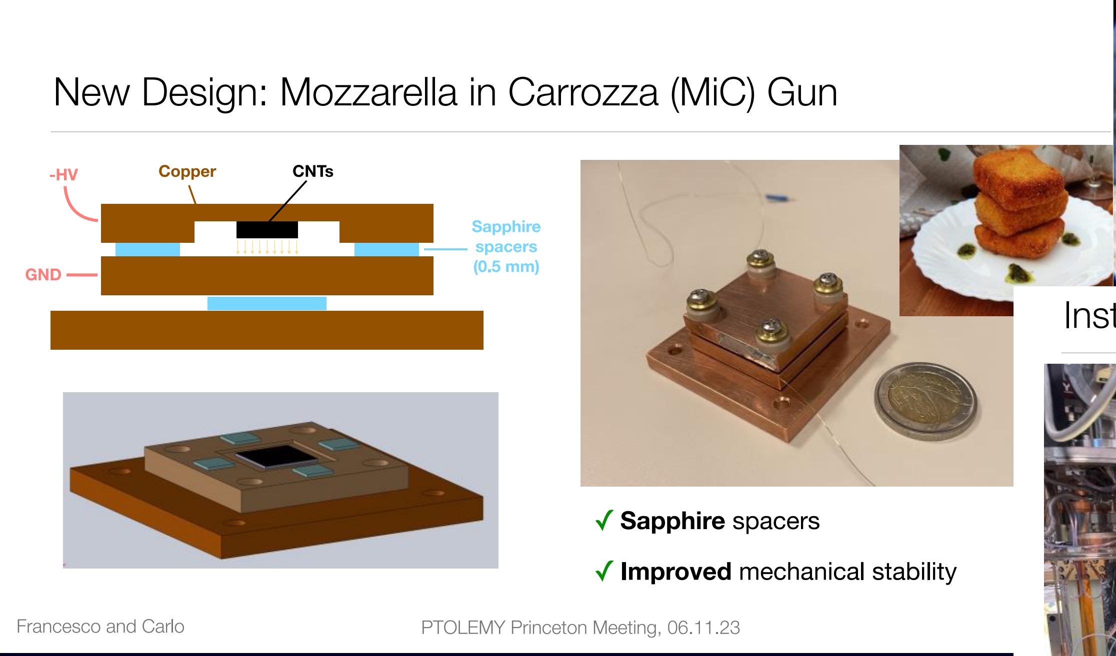
Carbon Nanotubes

Roma Tre



Field Emission





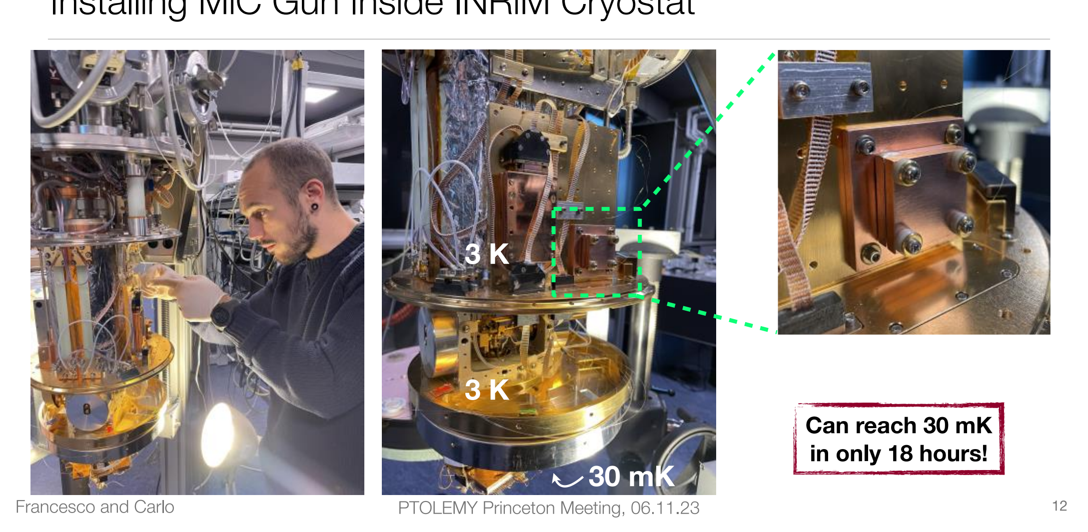
New Design: Mozzarella in Carrozza (MiC) Gun

✓ **Sapphire** spacers

✓ **Improved** mechanical stability

Francesco and Carlo

PTOLEMY Princeton Meeting, 06.11.23



Installing MiC Gun Inside INRiM Cryostat

Can reach 30 mK in only 18 hours!

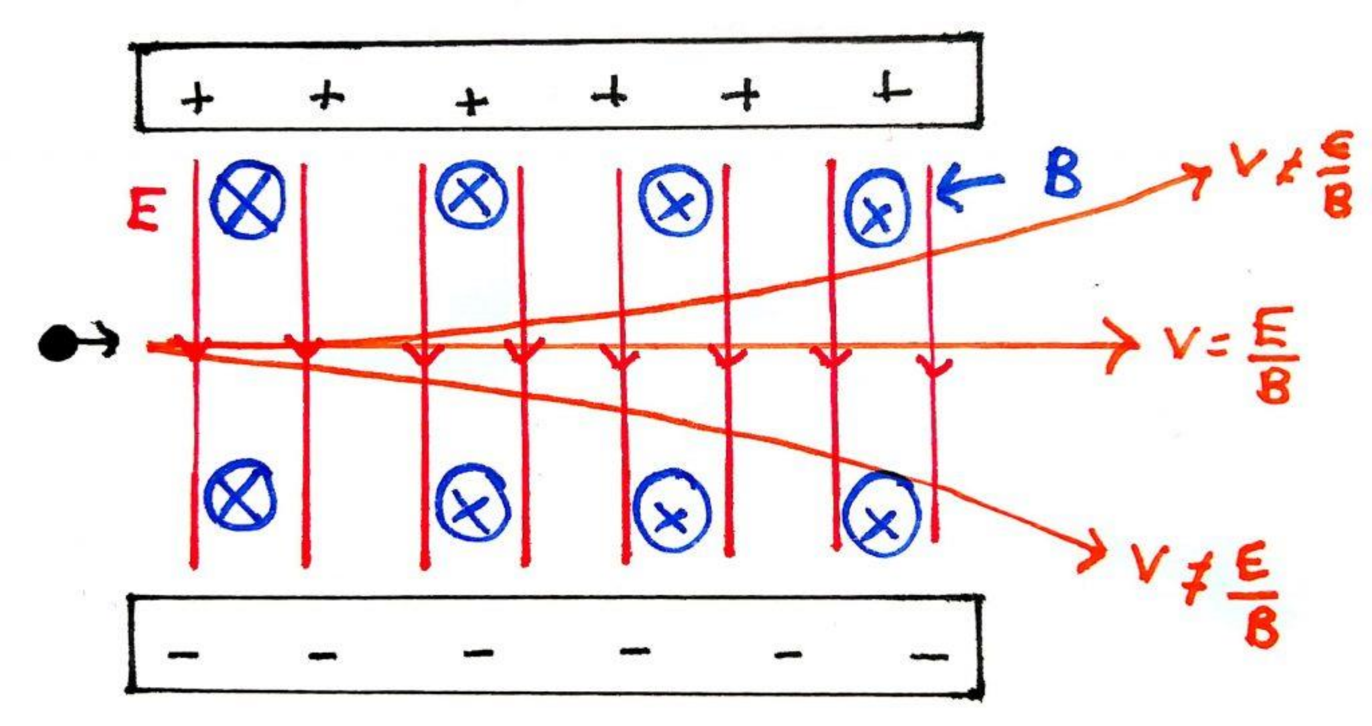
Francesco and Carlo

PTOLEMY Princeton Meeting, 06.11.23

12

Torino, Italy

Classic Velocity Selector

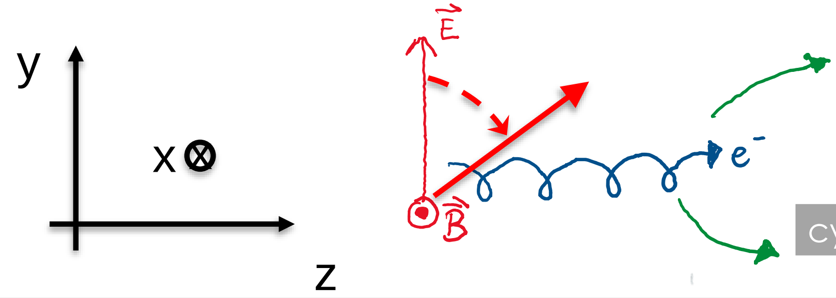


Is this the only way to select velocity?

PTOLEMY Filter Concept

Auke Pieter Colijn (PATRAS 2019)

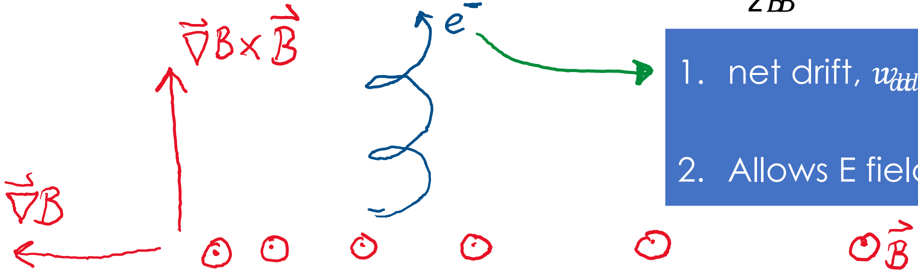
I: $\vec{E} \times \vec{C}$ drift



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

cyclotron motion – detectable RF

II: $\frac{\mu}{B^2}\vec{\nabla} C \times \vec{C}$ 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 (∥): $\frac{dT_\perp}{dt} = e\vec{E} \cdot \vec{v}_{drift}$

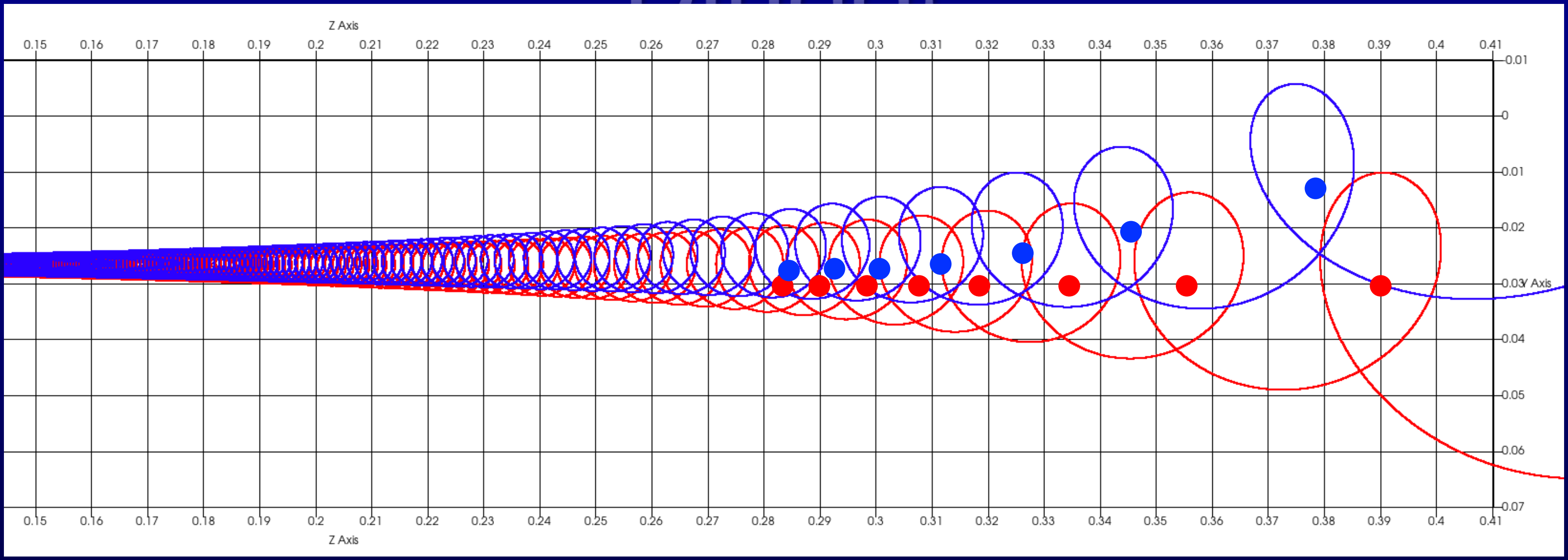
$$V^y_{E \times B}(z)|_{x,y=0} = \frac{E \times B}{B_x^2} = \frac{E_z B_x \hat{y}}{B_x^2} = \frac{E_z}{B_x}\hat{y}$$

$$V_{\nabla B}(z)|_{x,y=0} = -\frac{\mu \times \nabla_\perp B(z)}{qB(z)} = -\frac{\mu}{qB_x}\frac{dB_x}{dz}\hat{y}$$

Enforce zero drift in y (rotate E):

$$\xrightarrow{\text{yields}} \quad E_z(z)|_{y=0} = -\frac{\mu}{q}\frac{dB_x(z)}{dz}$$

Bingo!



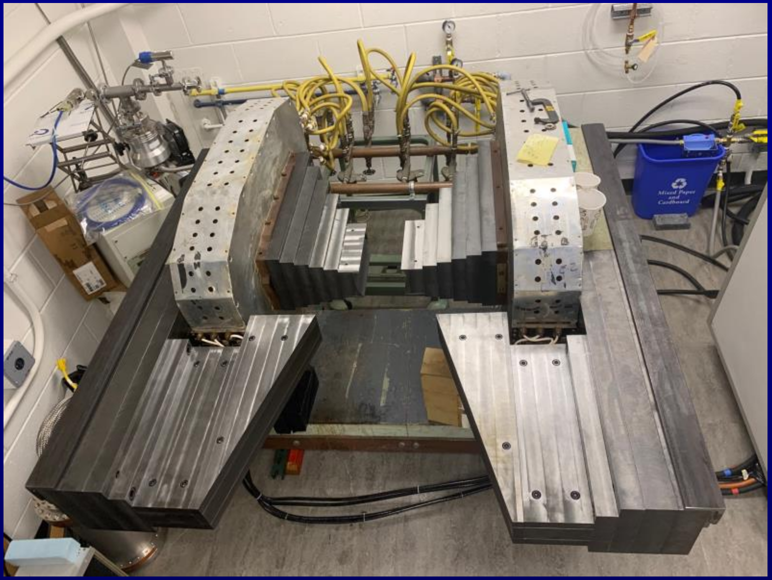
Selected velocity based on cyclotron drift

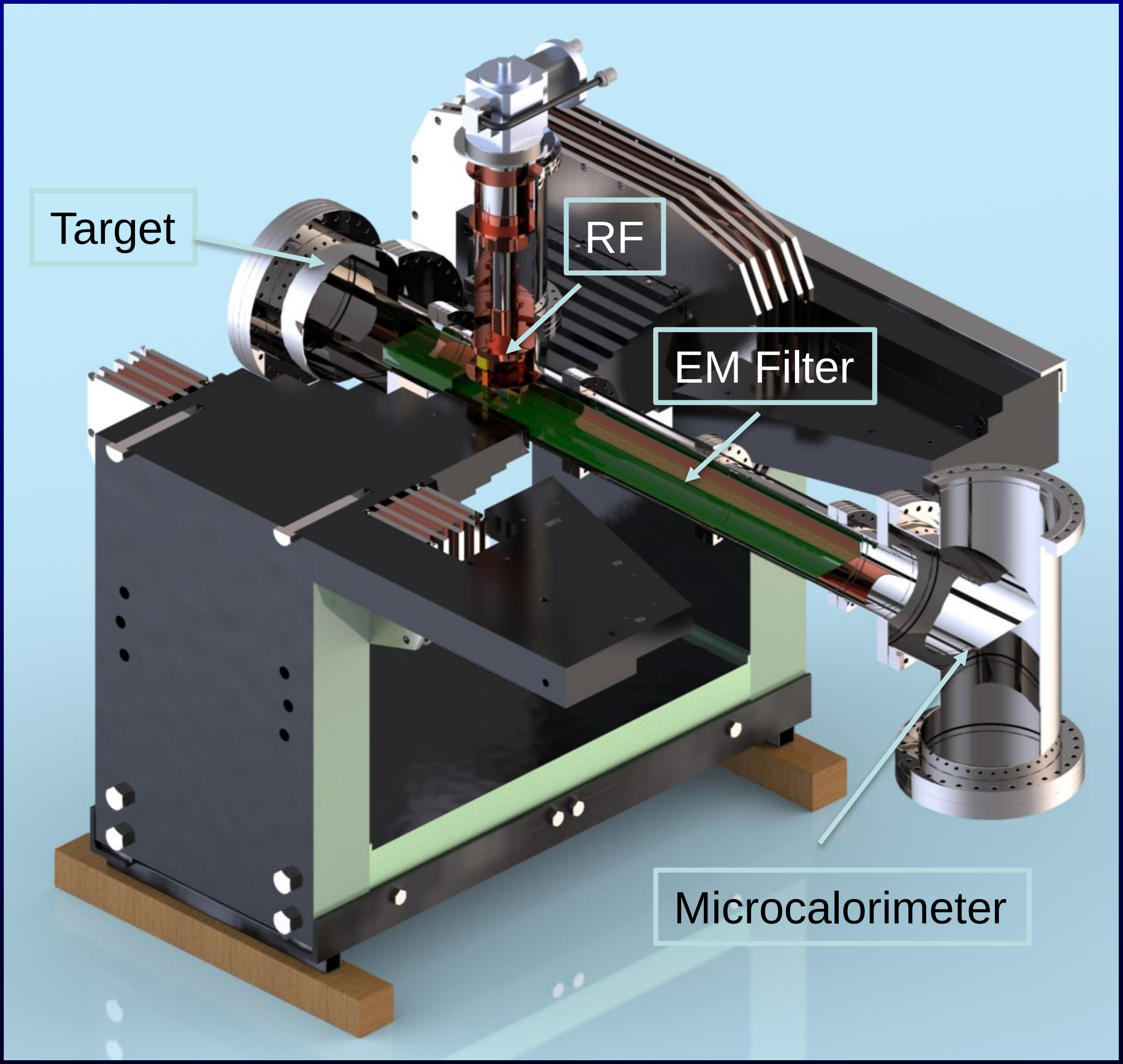
New type of particle accelerator (useful for fusion reactor heating)

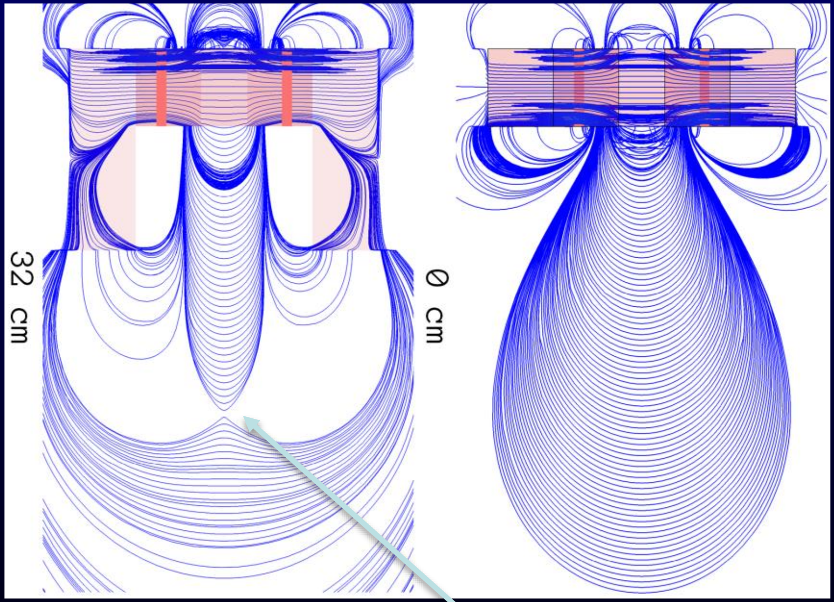
https://www.intechopen.com/chapters/82927

Filter R&D Development Setup

Andi Tan (Princeton)



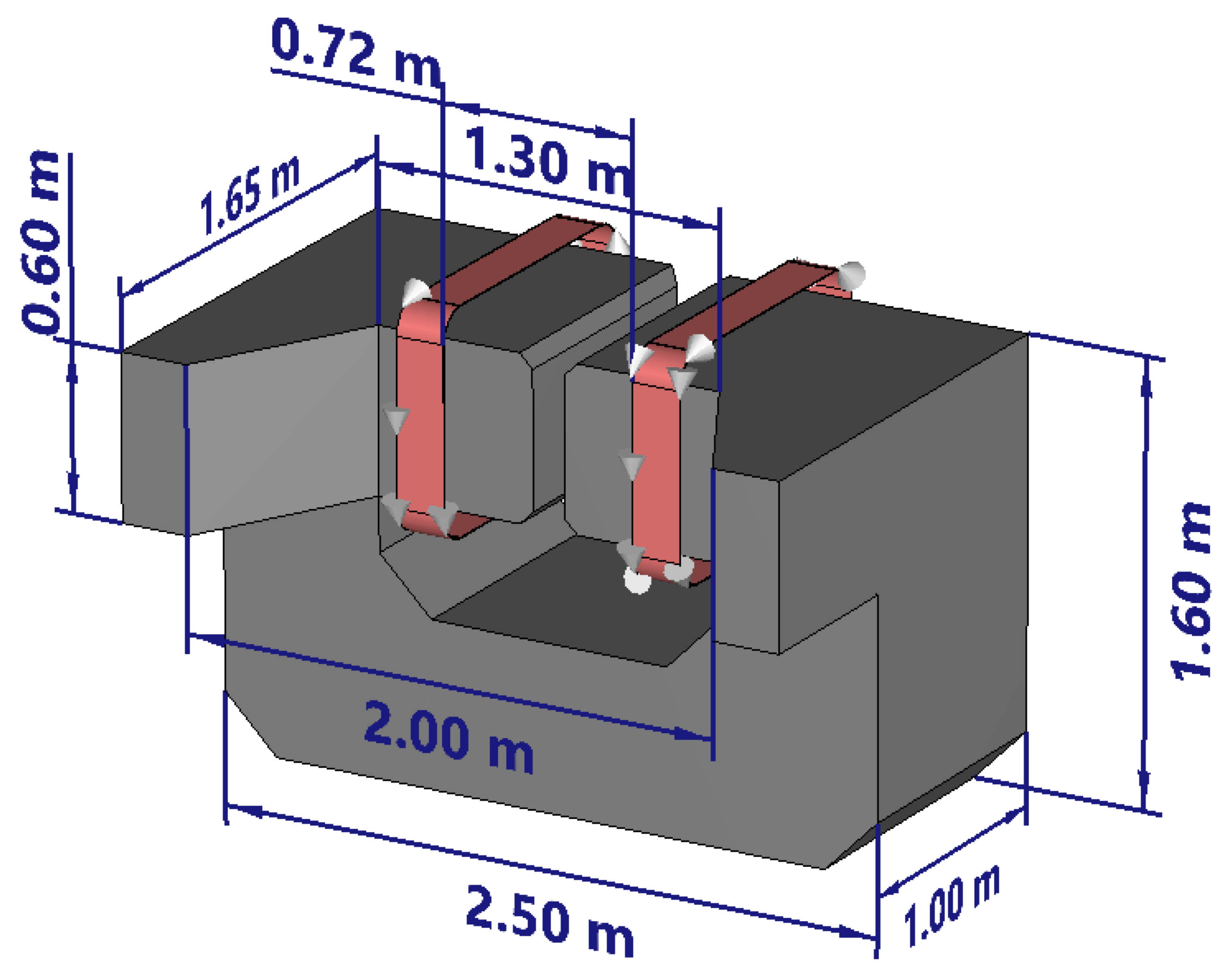


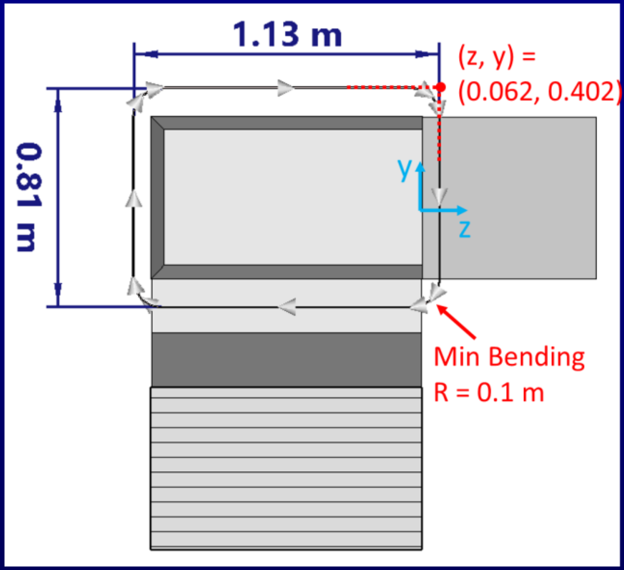


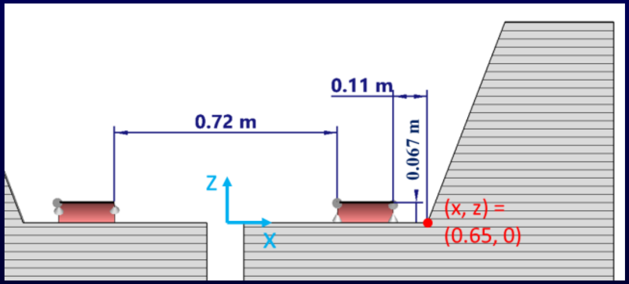
Wonyong Chung (Princeton)

Zero field (location for TES microcalorimeter)

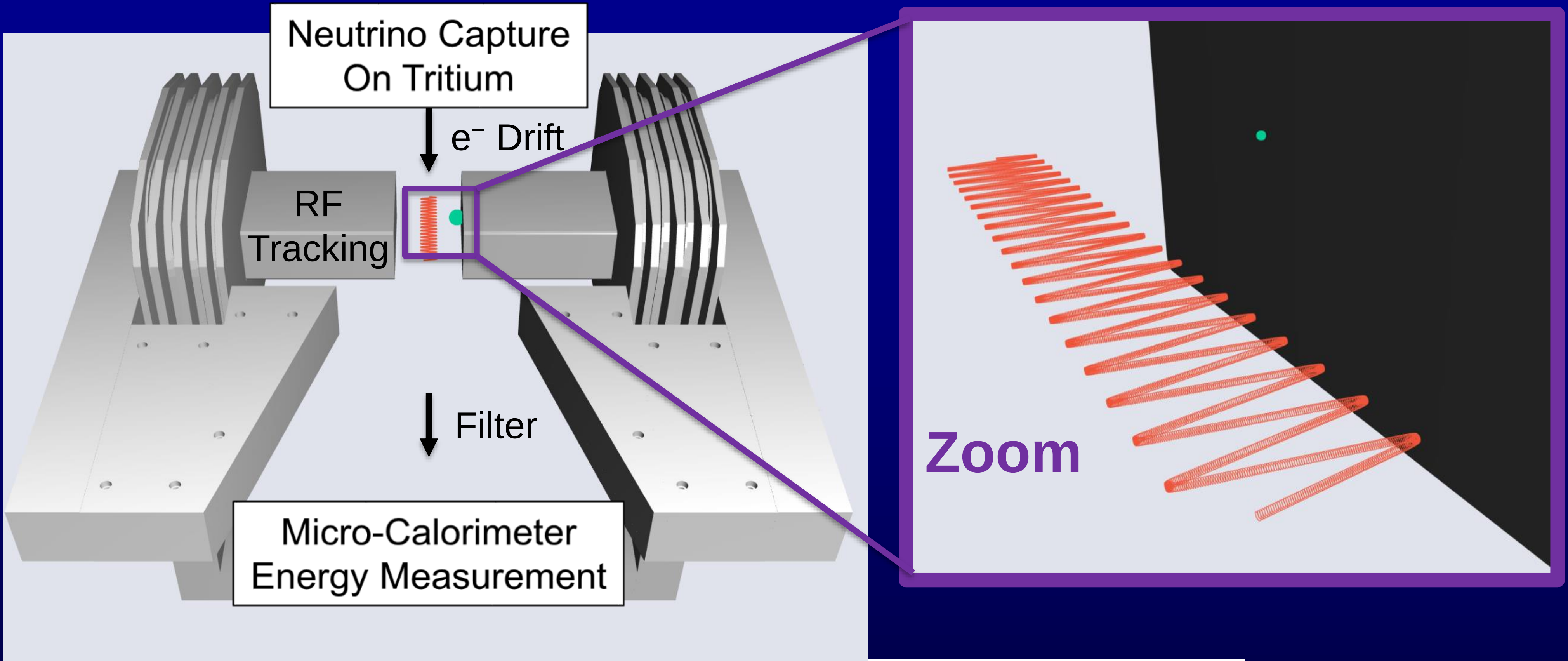
ASG-SupraSys Magnet @LNGS







RF Tracking of Semi-Relativistic Electrons



Neutrino Capture On Tritium

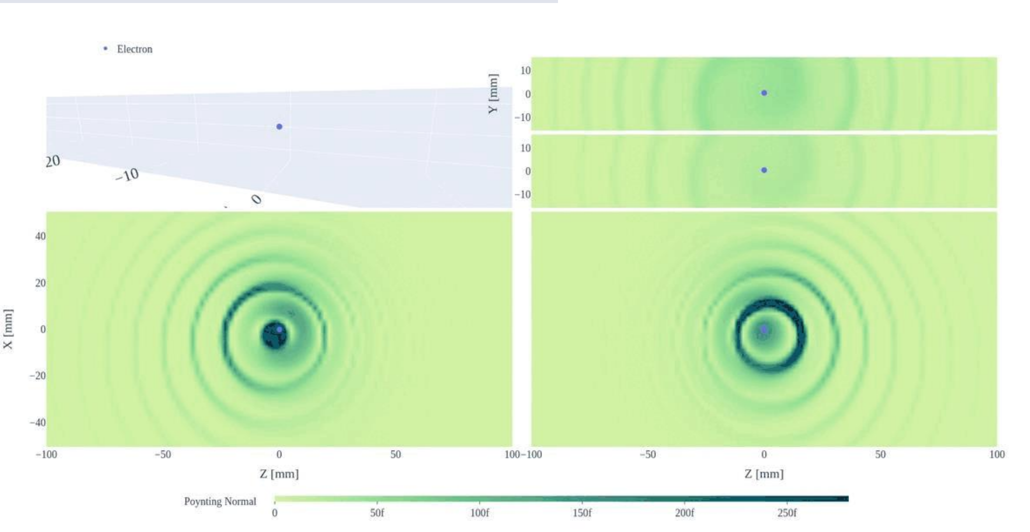
e⁻ Drift

RF Tracking

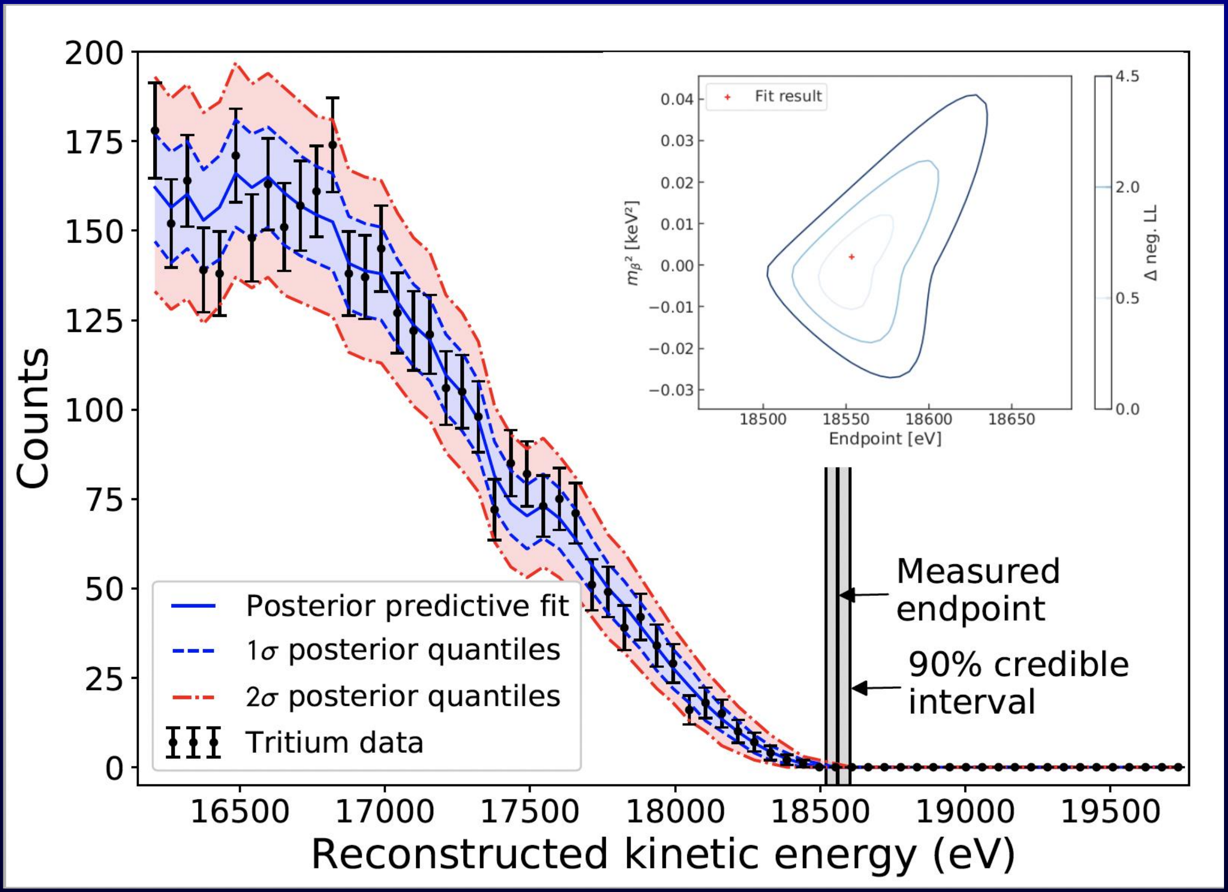
Filter

Micro-Calorimeter Energy Measurement

Zoom



Recent Project 8 Tritium Measurement



https://arxiv.org/abs/2203.07349

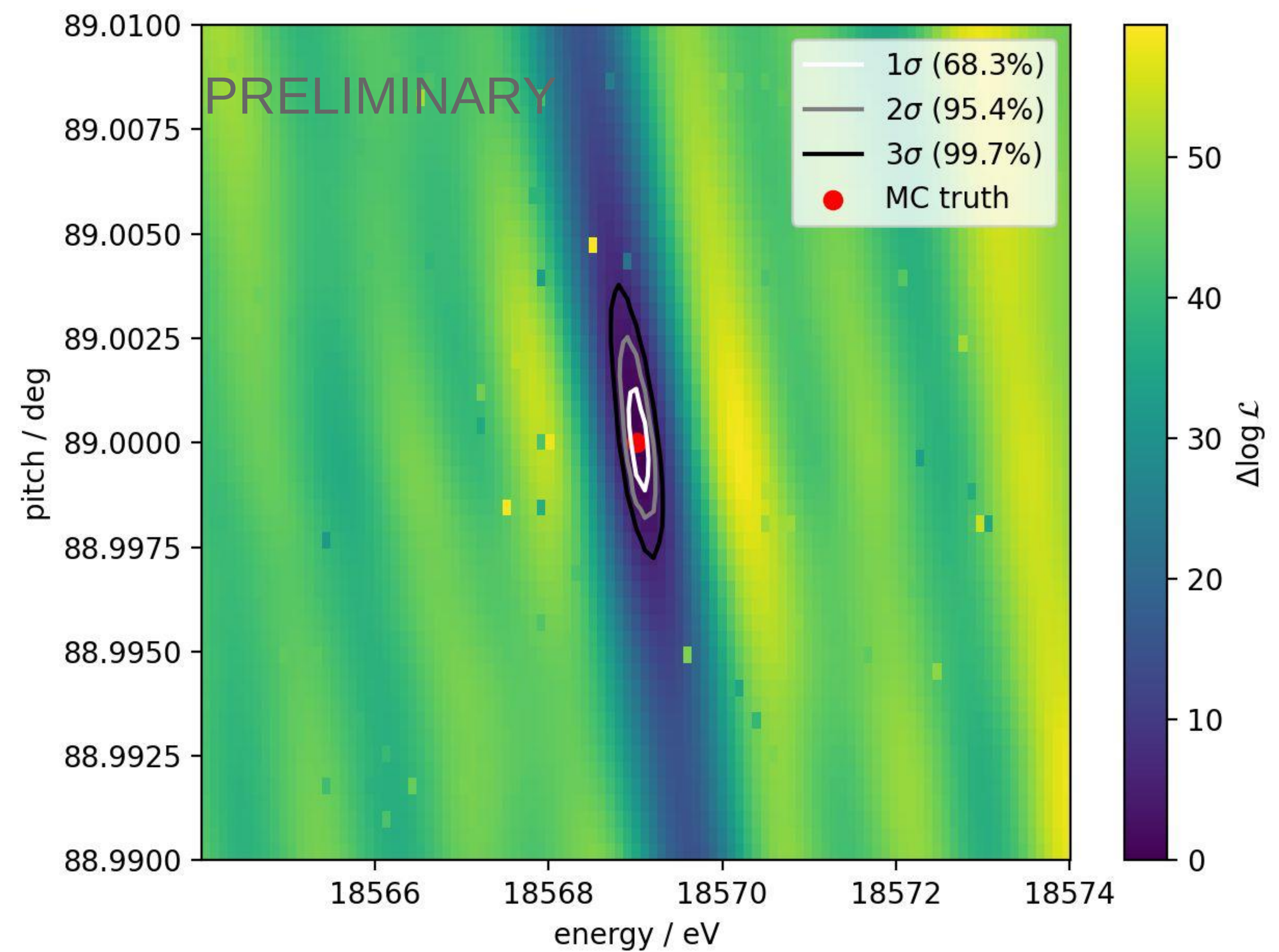
RF measurement background levels extremely low.

No events observed above endpoint, Setting upper limit on background rate

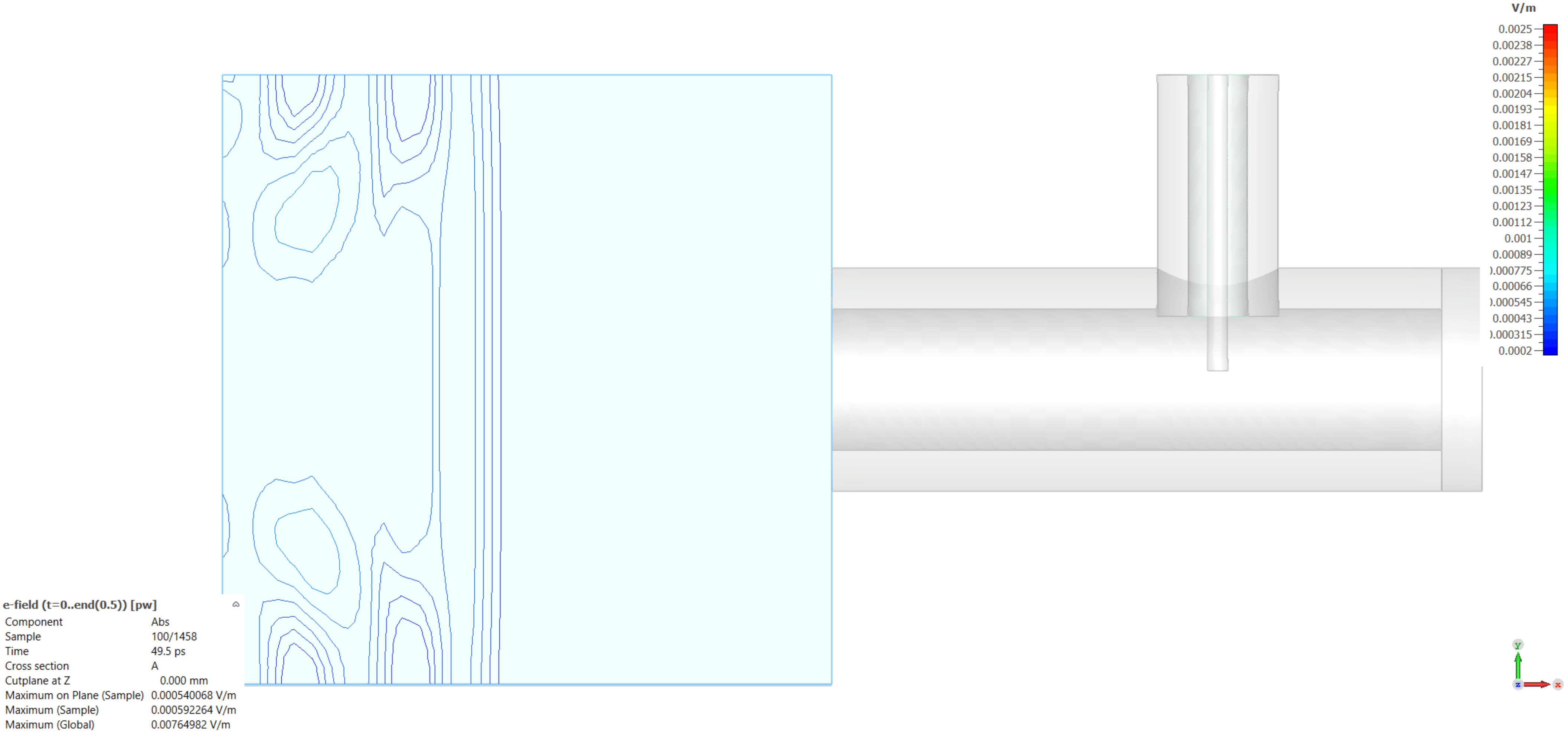
< 3x10^{-10} /eV/s (90% CL)

→ < 1 event per eV in 100 years!

Great Opportunities to Learn and Collaborate with Project 8



RF Antenna Simulations

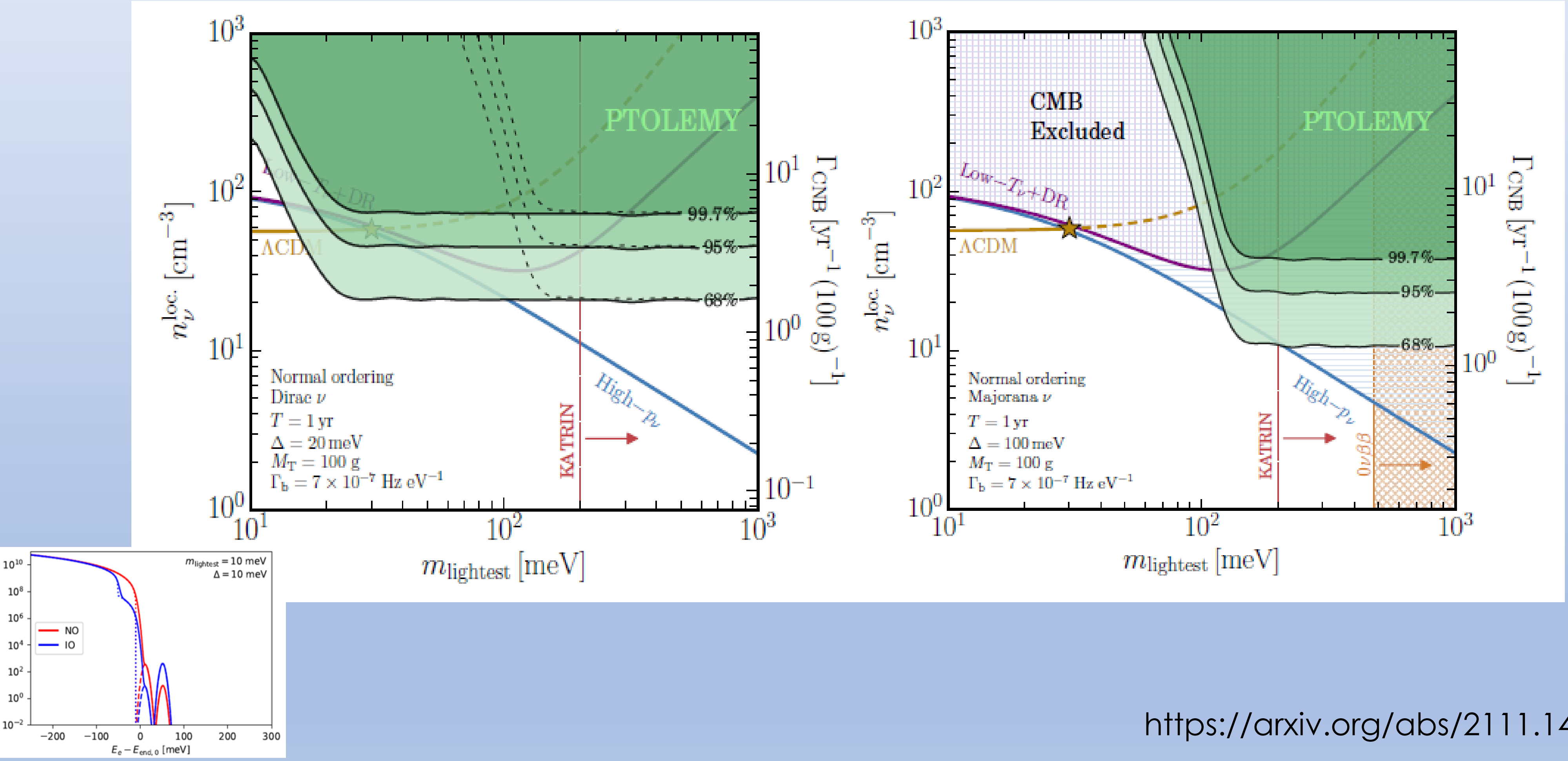


e-field (t=0..end(0.5)) [pw]

Component	Abs
Sample	100/1458
Time	49.5 ps
Cross section	A
Cutplane at Z	0.000 mm
Maximum on Plane (Sample)	0.000540068 V/m
Maximum (Sample)	0.000592264 V/m
Maximum (Global)	0.00764982 V/m

Yuno Iwasaki

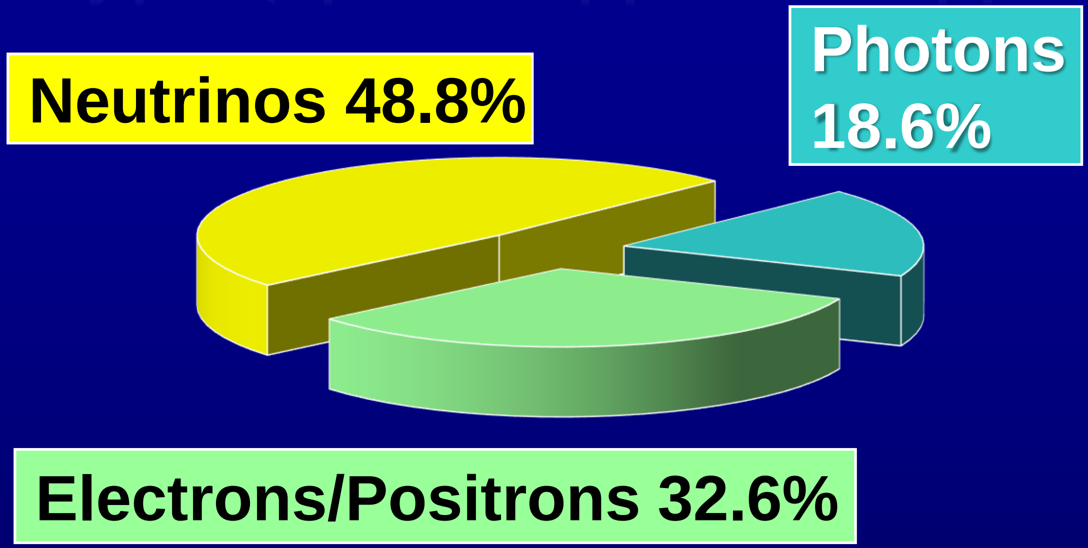
PTOLEMY: $C\nu B$ expected performance



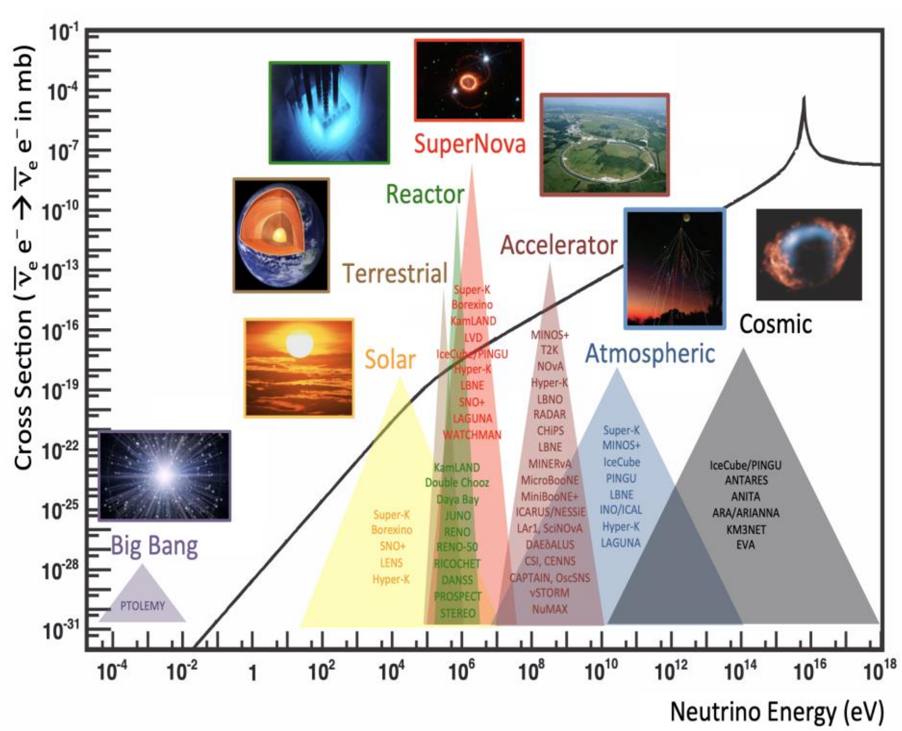
https://arxiv.org/abs/2111.14870

Neutrino mass sensitivity exploiting atomic scale Graphene effects at endpoint (in progress)

Neutrinos: Unsung Heroes of the Universe



Neutrino Decoupling
(t=1 second)



<u>Leading role in early Universe</u>

photon+**neutrino**-to-baryon ratio

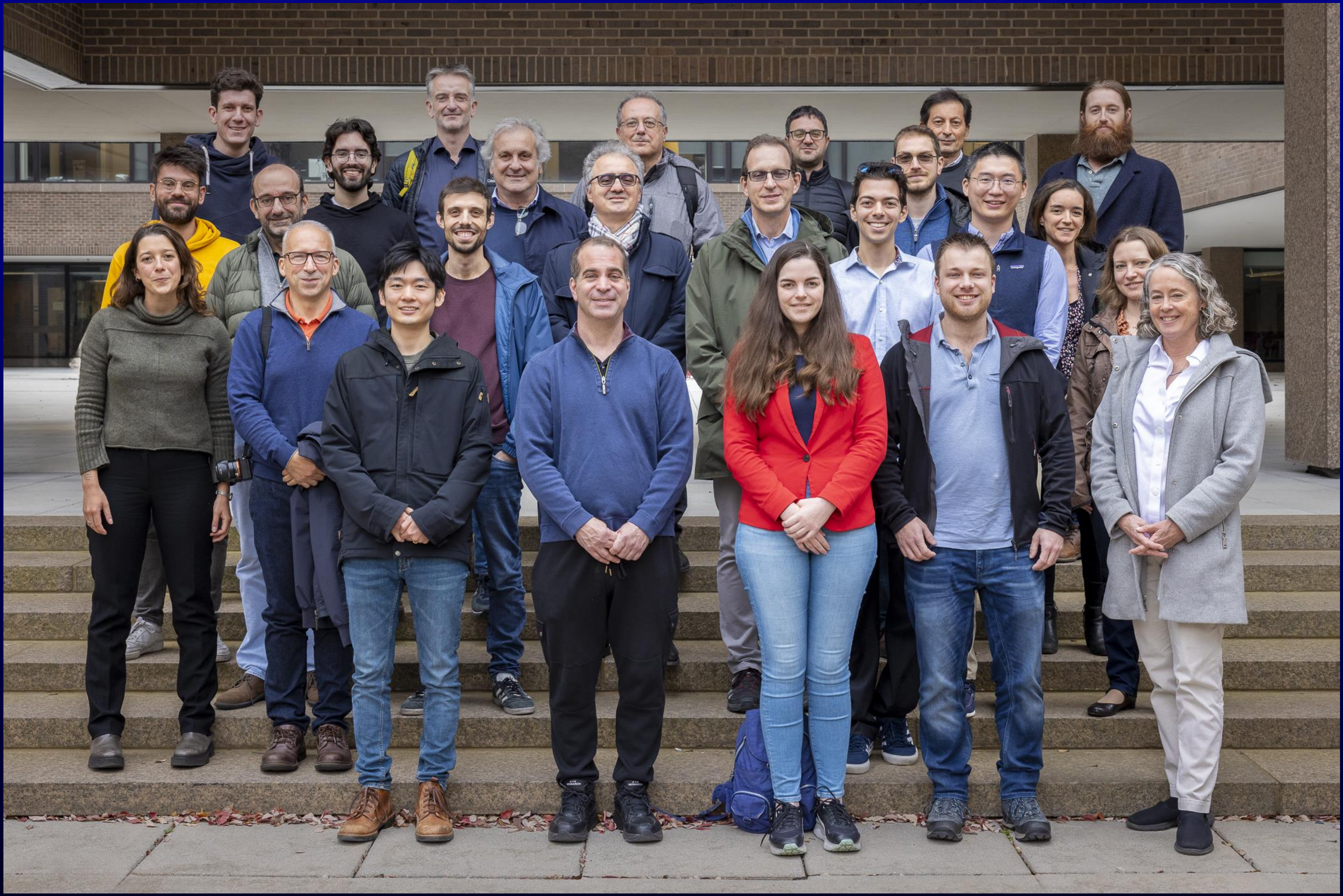
Matter-(Photon+**Neutrino**) Equality

<u>And in the current Universe</u>

Solar cooling/Supernovae

<u>And potentially much more in the dark sector</u> (???)

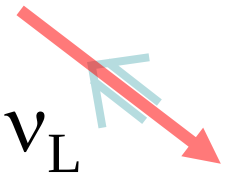
PTOLEMY Workshop @Princeton/NYU

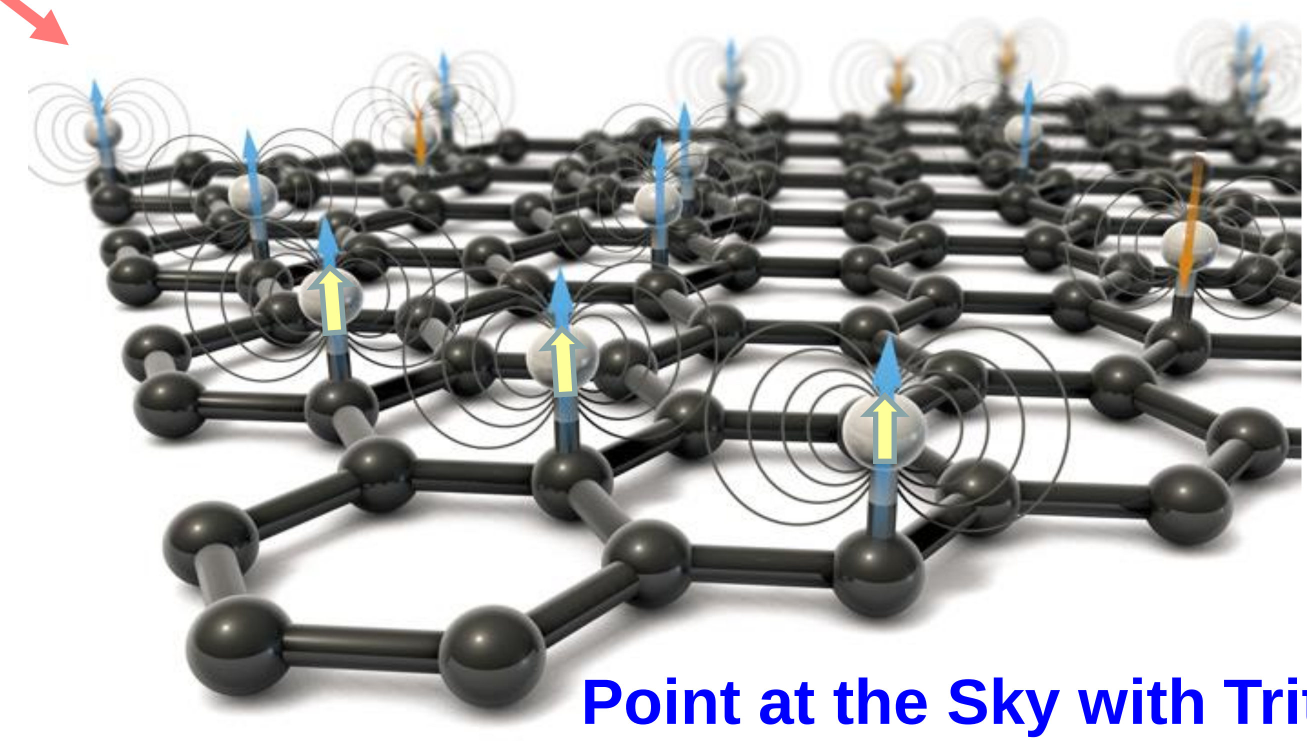


Princeton University
December 7, 2023

ADDITIONAL SLIDES

Polarized Tritium Target



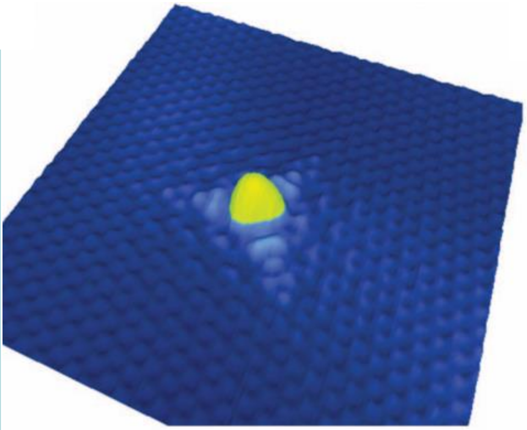


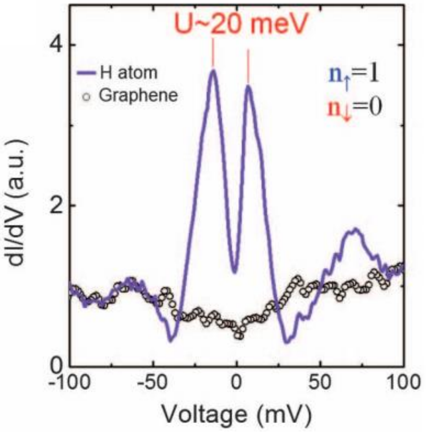
Lisanti, Safdi, CGT, 2014.
10.1103/PhysRevD.90.073006
Akhmedov, 2019.
10.1088/1475-7516/2019/09/031

Point at the Sky with Tritium Nuclear Spin ⇧

Detection (capture) of cold neutrinos:

$$\mathbf{d\sigma/d\cos\theta\ (v/c) \sim (1+\cos\theta)}$$



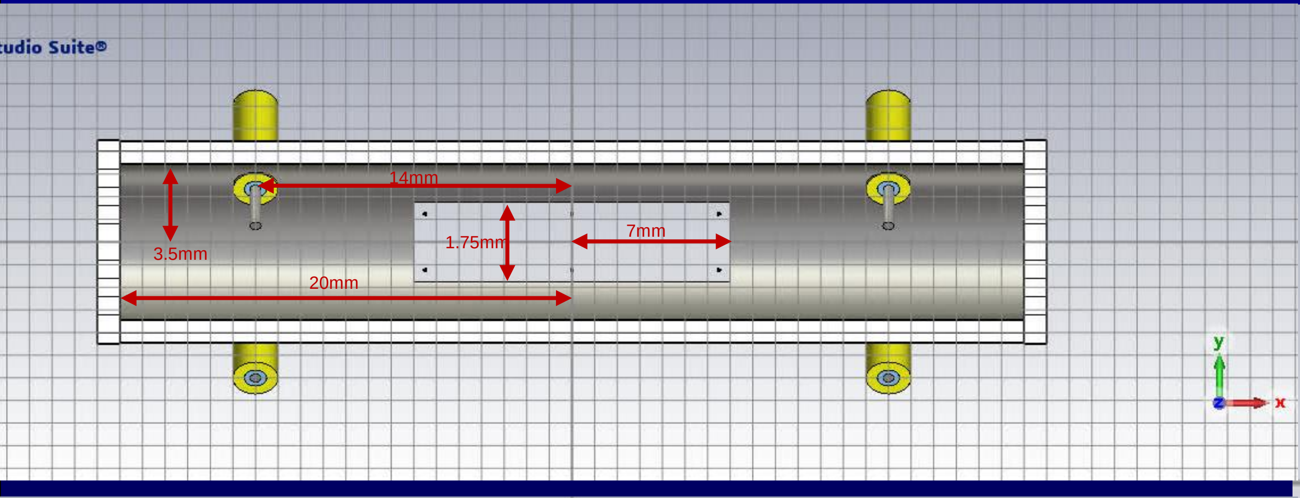


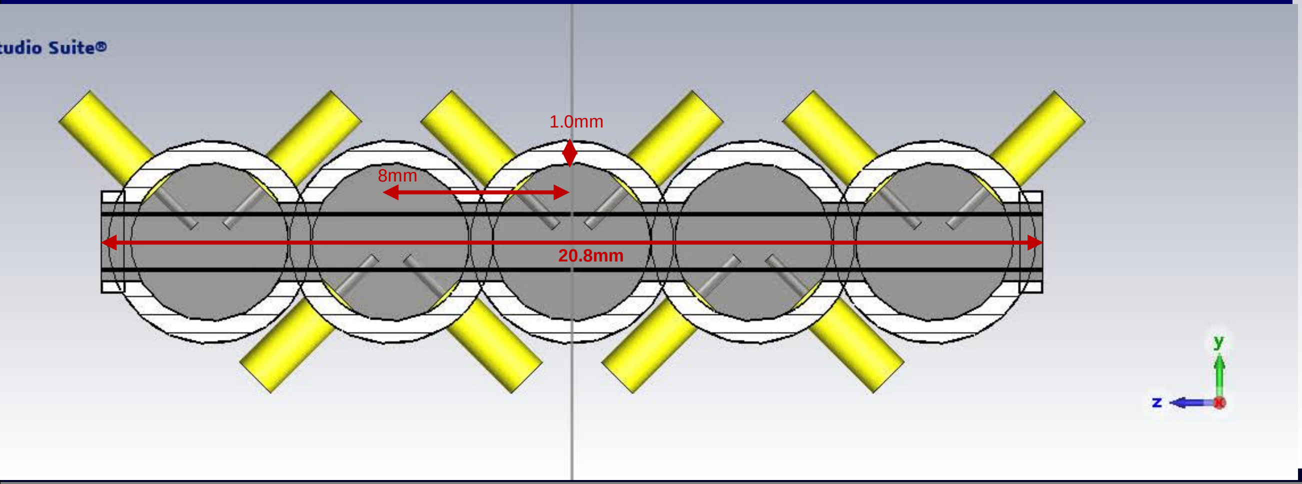
Hydrogen doping on graphene reveals magnetism

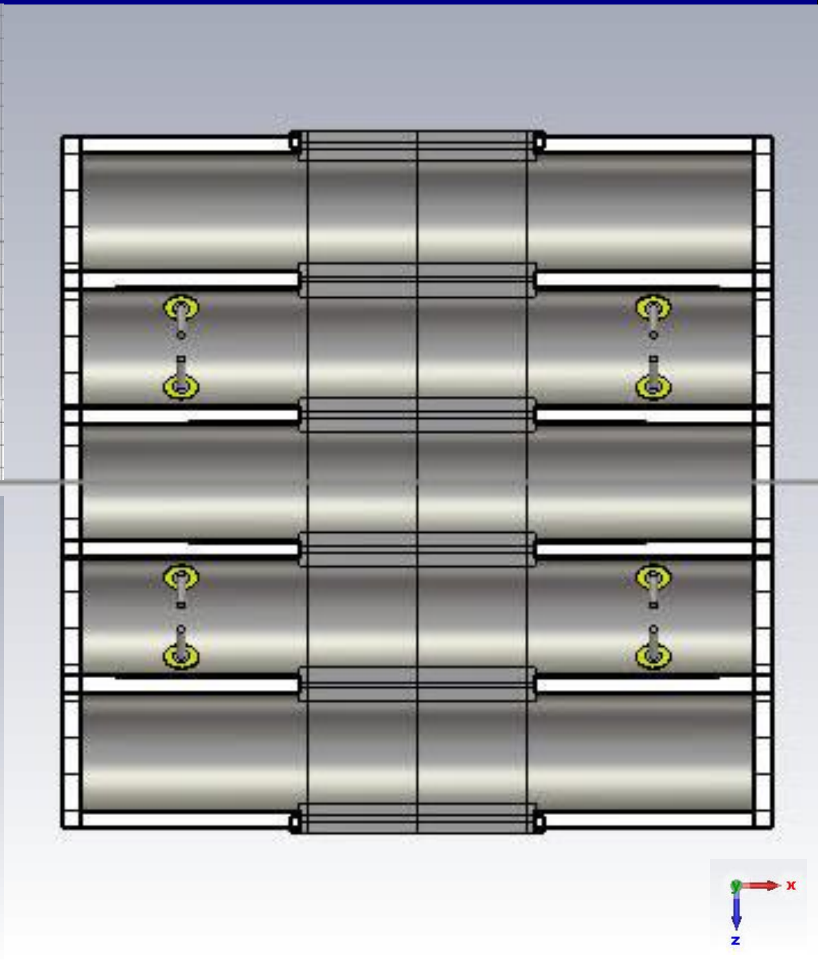
Gonzalez-Herrero, H. *et al.* Atomic-scale control of graphene magnetism by using hydrogen atoms. *Science (80).* **352,** 437–441 (2016).

New Ideas for Enhancing RF Detection

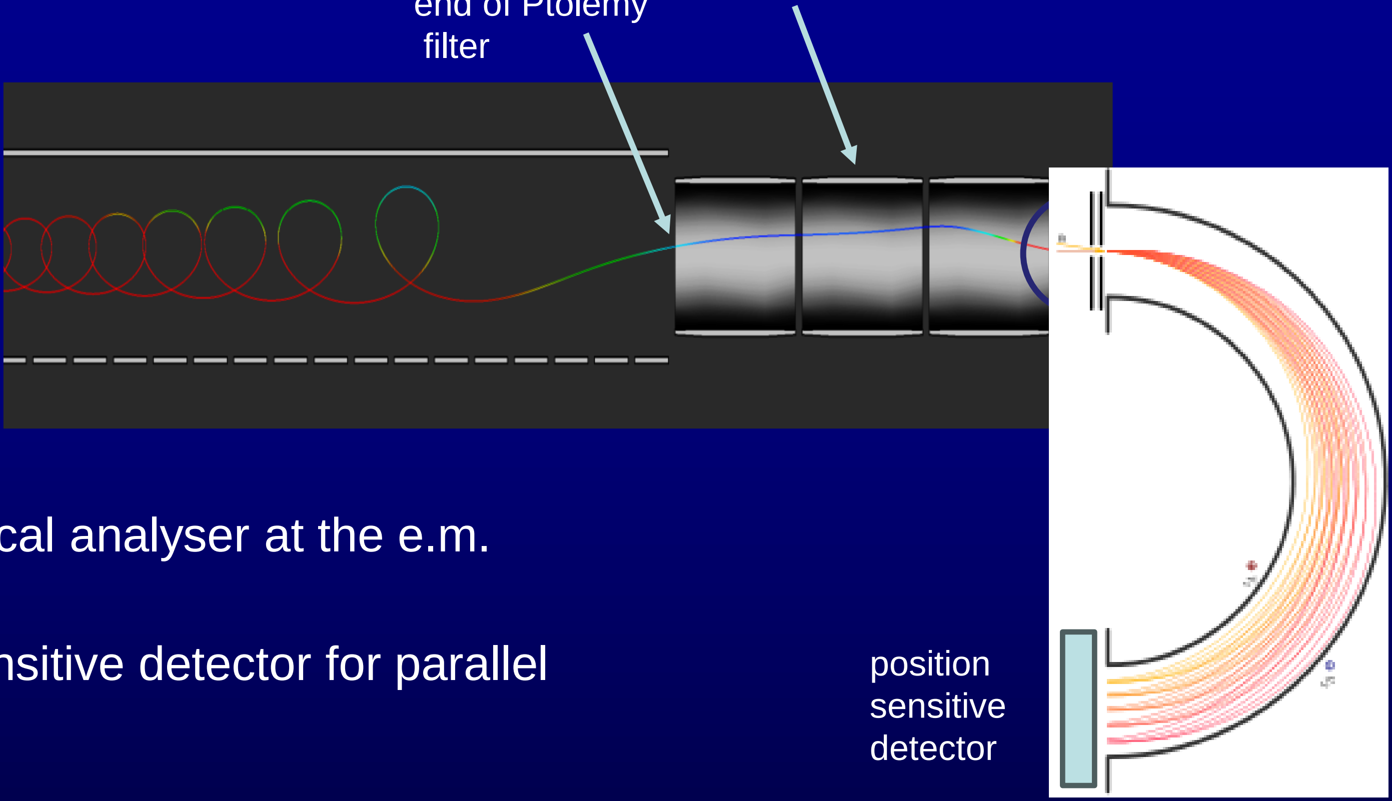
Small cavity: Longitudinal reconstruction







Electrostatic Electron Analyser:
another approach to high resolution measurement



end of Ptolemy filter

Einzel lenses

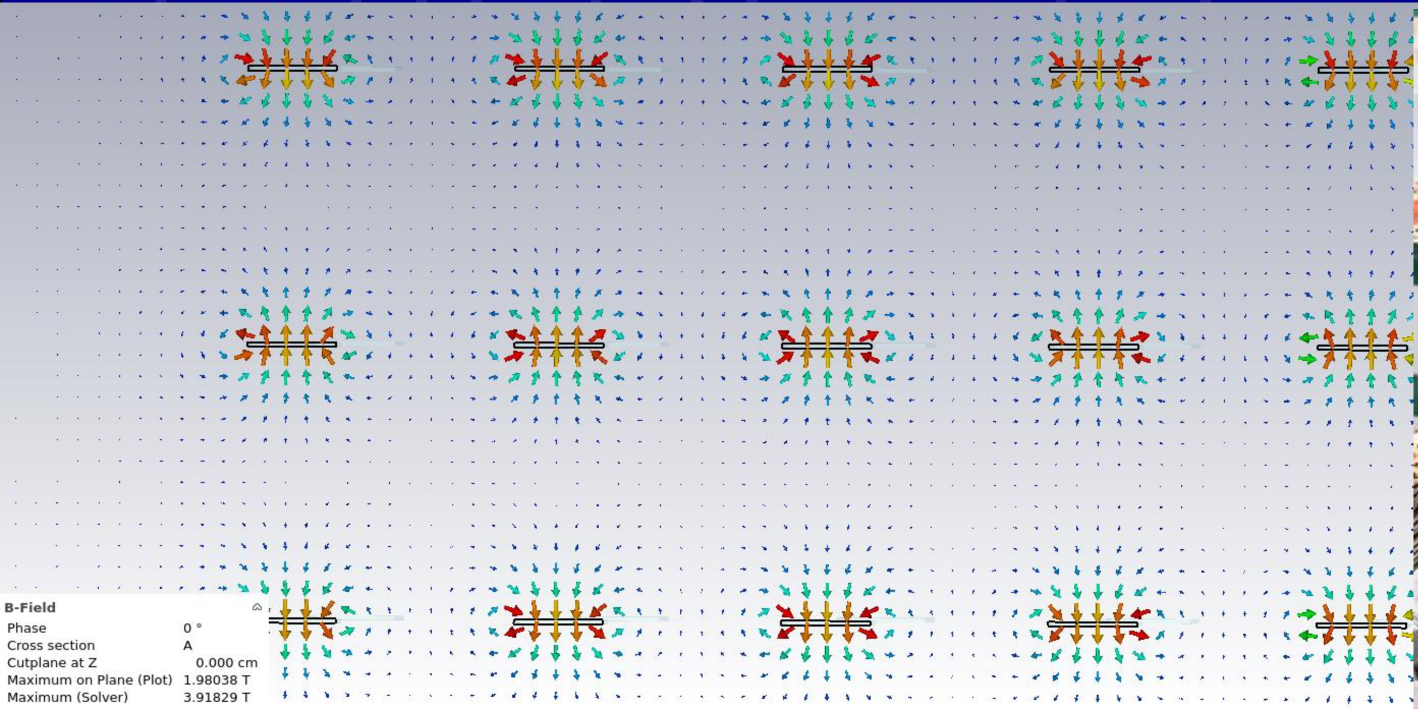
hemispherical analyser

position sensitive detector

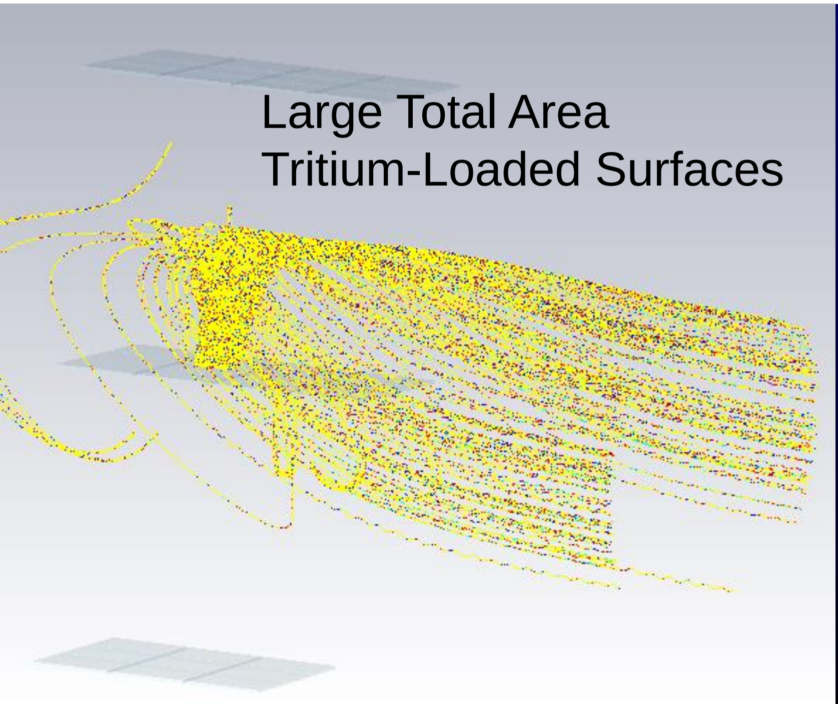
- hemispherical analyser at the e.m. filter end
- position sensitive detector for parallel acquisition

	Phoibos 225	**Phoibos 100**	**EW-4000**
Mean radius (mm)	225	100	200
Detector type	2D DLD	2D DLD	2D DLD
Pass energy (eV)	Up to 500	Up to 500	Up to 500
Energy window	9% of P.E.	20% of P.E.	
Resolution	< 1meV	< 3 meV	< 2 meV
Acceptance angle	±15°	±15°	±30°

First High Capacity Target Designs



B-Field
Phase 0 °
Cross section A
Cutplane at Z 0.000 cm
Maximum on Plane (Plot) 1.98038 T
Maximum (Solver) 3.91829 T



Large Total Area
Tritium-Loaded Surfaces