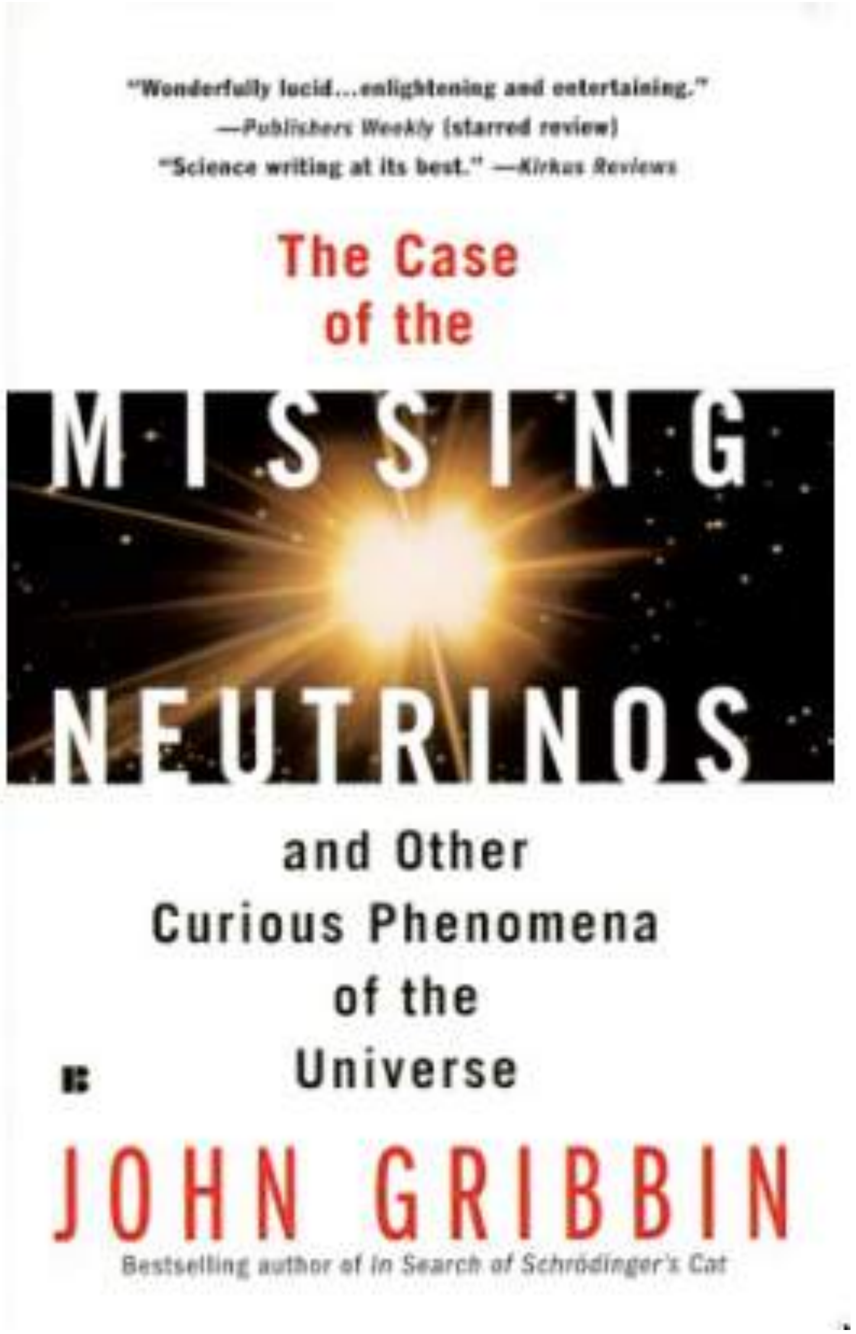
Neutrino Experiment

Flavio Gatti, University and INFN of Genova

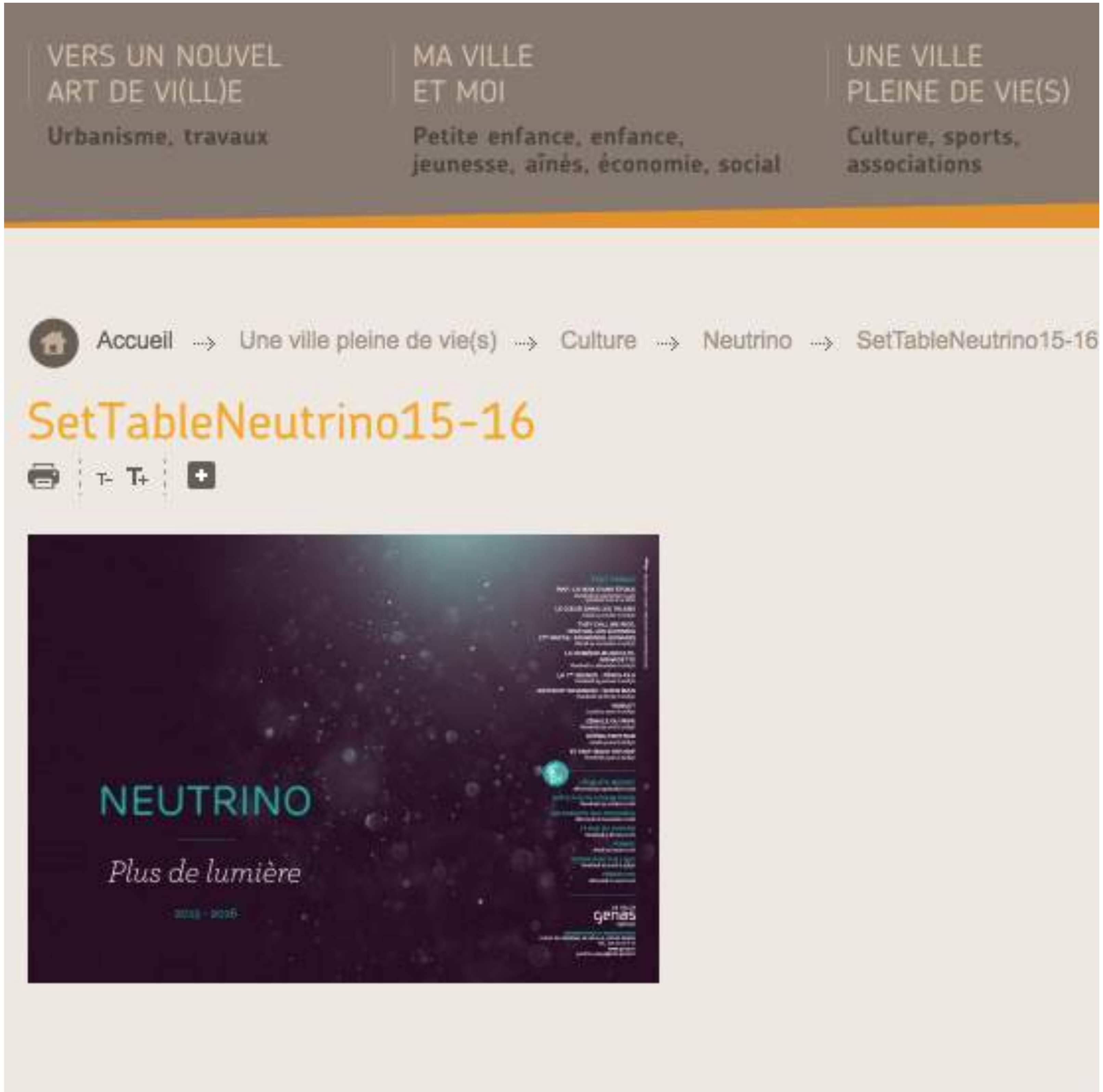
Neutrino

This word is now very popular!



Books, TV, Newspaper, Web…

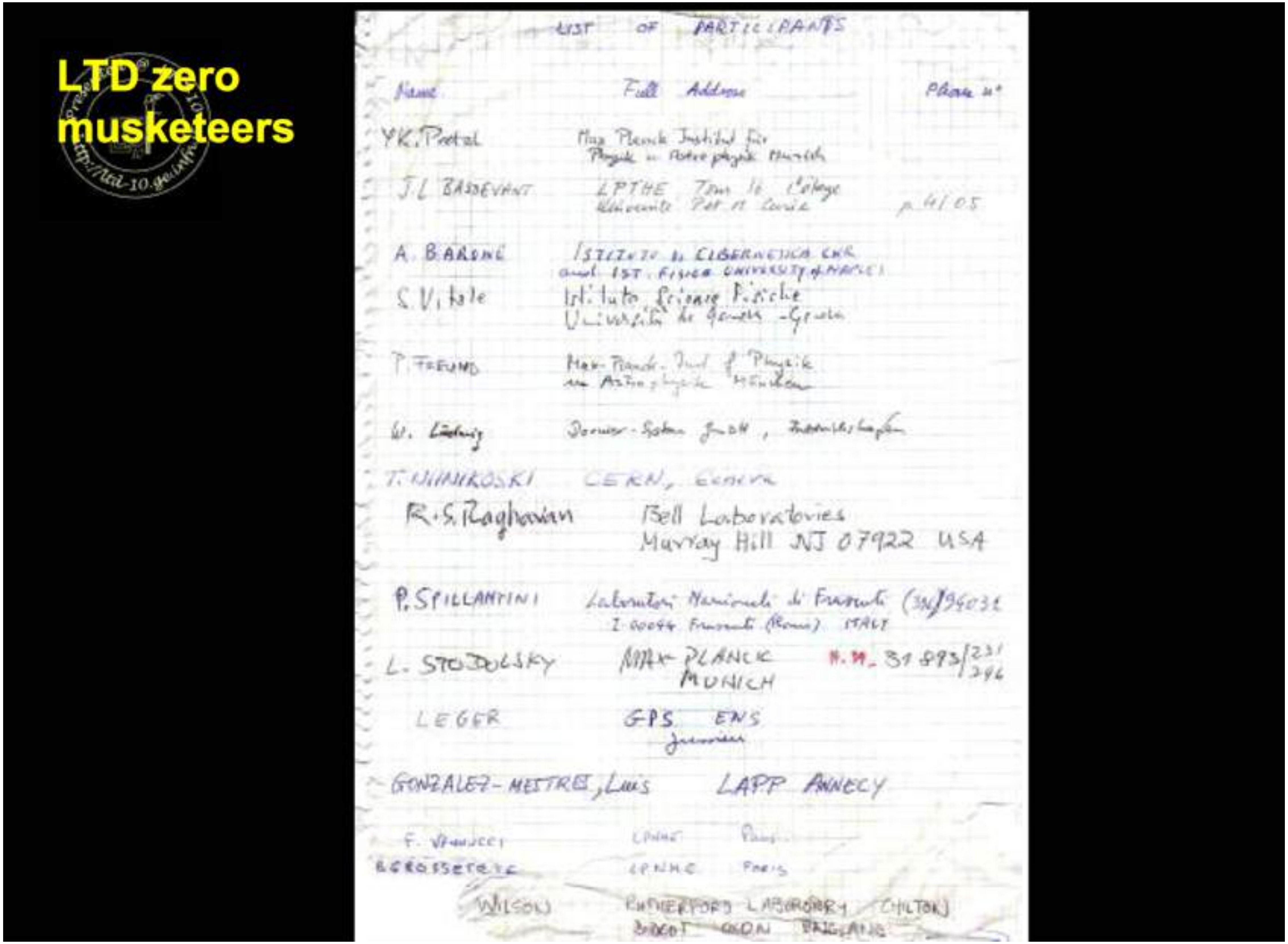
… and it is cool!



My son too!

- Edoardo:"Daddy, how the spacecraft on Pluto works? I don't see solar cells!
- Flavio: " Uhm, it's complicate… nuclear generator…"
- Edoardo: " I've understood: neutrinos push the spacecraft"
- Flavio: "Oh never considered - I Think-. If I consider the cross section against the solar neutrinos, the solar wind, the magnetic moment and maybe the coherent scattering… neutrino truster? "
  -I say- I am too old, it is a physics for the new generation

Neutrino and DM has driven the first steps of the Low Temperature Detector Community



LIST OF PARTICIPANTS

Name	Full Address	Phone n°
YK. Pretzl	Max Planck Institut für Physik u. Astrophysik München	
J.L. BASDEVANT	LPTHE [illegible] Université P. et M. Curie	[illegible]
A. BARONE	ISTITUTO di CIBERNETICA CNR and IST. FISICA UNIVERSITY of NAPLES	
S. Vitale	Istituto [illegible] Fisiche Università di Genova - Genova	
P. FREUND	Max-Planck-Inst. f. Physik [illegible] München	
[illegible]	[illegible]	
T. NIINIKOSKI	CERN, GENEVA	
R.S. Raghavan	Bell Laboratories Murray Hill NJ 07922 USA	
P. SPILLANTINI	Laboratori Nazionali di Frascati I-00044 Frascati (Roma) ITALY	[illegible]
L. STODOLSKY	MAX-PLANCK MUNICH	[illegible]
LEGER	GPS ENS [illegible]	
GONZALEZ-MESTRE, Luis	LAPP ANNECY	
F. [illegible]	LPNHE Paris	
[illegible]	LPNHE PARIS	
WILSON	RUTHERFORD LABORATORY CHILTON DIDCOT OXON ENGLAND	

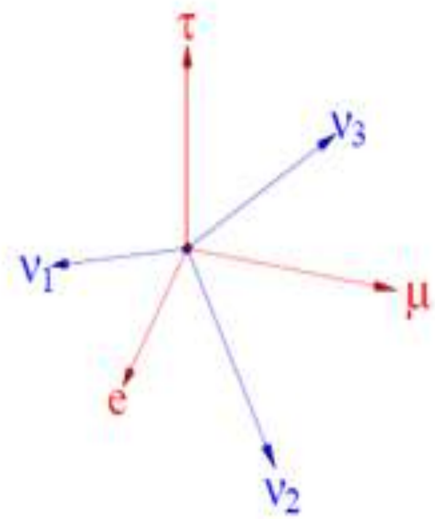
Low Temperature Detector 1st Workshop

What we know.

- Since the the flavour oscillations paradigm has been proved, a renewed interest for investigating the absolute mass scale is grown.

- The paradigm is based on kinematics of a system in which Mass eigenstates are rotated respect to the F

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \end{pmatrix} .$$



- Solar neutrino undertakes flavour oscillation travelling away from the source. The probability detecting same flavour

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2 \frac{\Delta m_{21}^2 L}{4E} - \sin^2 2\theta_{13} \left[c_{12}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} + s_{12}^2 \sin^2 \frac{\Delta m_{32}^2 L}{4E} \right] .$$

- This holds if the mass is not zero

What we don’t know

After more than 80 years after the Fermi theory of β decay and the neutrino hypothesis

- Dirac or Majorana Neutrino?
- Normal (NH) or inverted mass ordering (IH)?
- The absolute mass scale ?
- If the Majorana nature can be established, what is the CP violating phase
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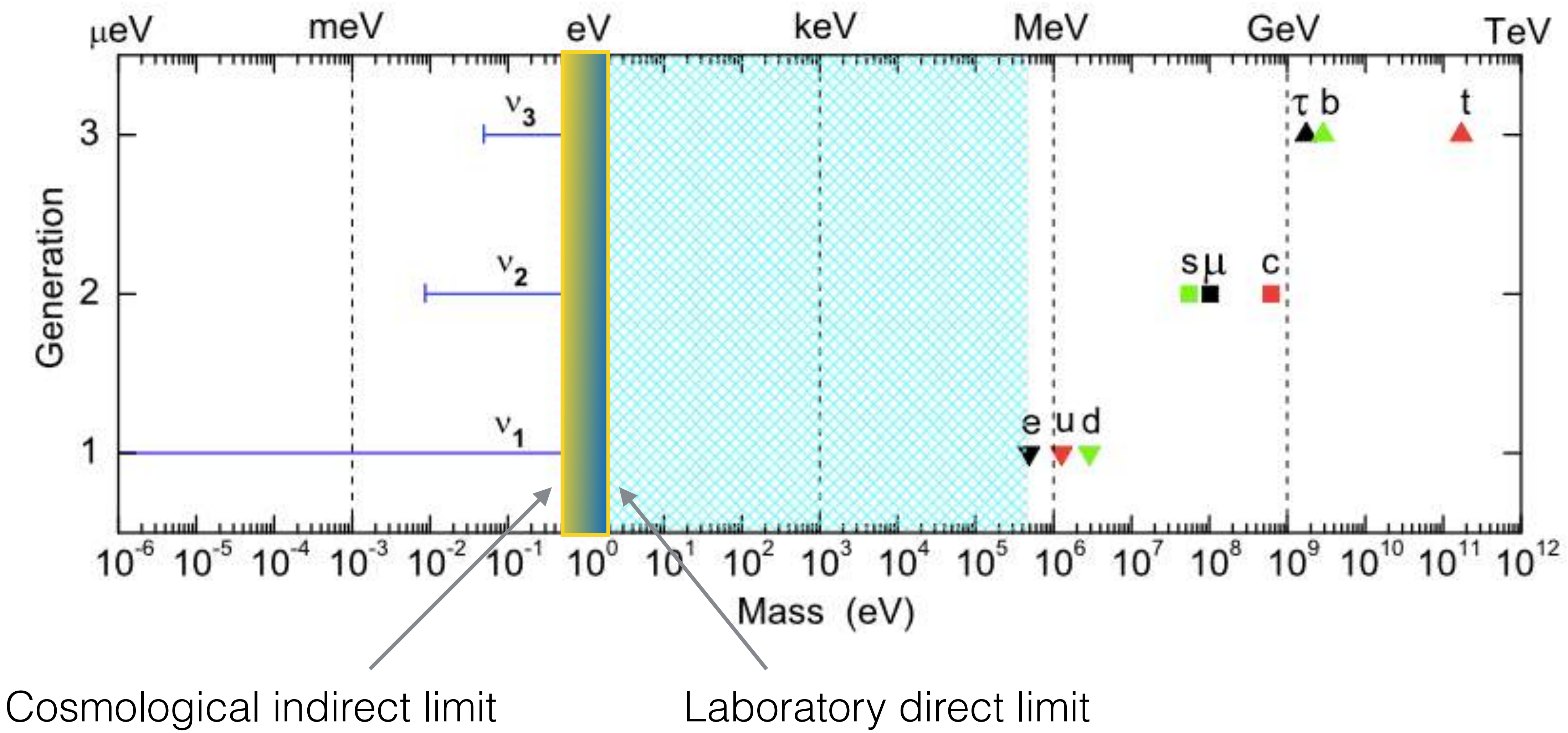
- Extra light or heavy sterile neutrinos?
- Neutrino has spin, what about the magnetic moment?
- Theory predicts Coherent Nuclear Scattering never observed

The mass spectrum



Kinematical methods

- β decay: $m_j \neq 0$ affect β−spectrum endpoint. Sensitive to the "effective electron neutrino mass":
  $\mathbf{m}_\beta = \{ \Sigma_j m_j^2 |U_{ej}|^2 \}^{1/2}$ Flavor-Mass Mixing Parameter

- 0ν2β decay: can occur if $m_j \neq 0$. Sensitive to the "effective Majorana mass":
  $\mathbf{m}_{\beta\beta} = \{ \Sigma_j m_j |U_{ej}|^2 e^{i\varphi_j} \}$ Flavor-Mass Mixing parameter + imaginary phase

- Cosmology: $m_j \neq 0$ can affect large scale structures in (standard) cosmology constrained by CMB and not CMB (LSS,Lyα) data. Sensitive to:
  $\mathbf{m} = \Sigma_j m_j$ Flavor-Mass Mixing independent

Mass scale

- The absolute mass scale of neutrinos remains today an open question subject to experimental investigation from both particle physics and cosmology.

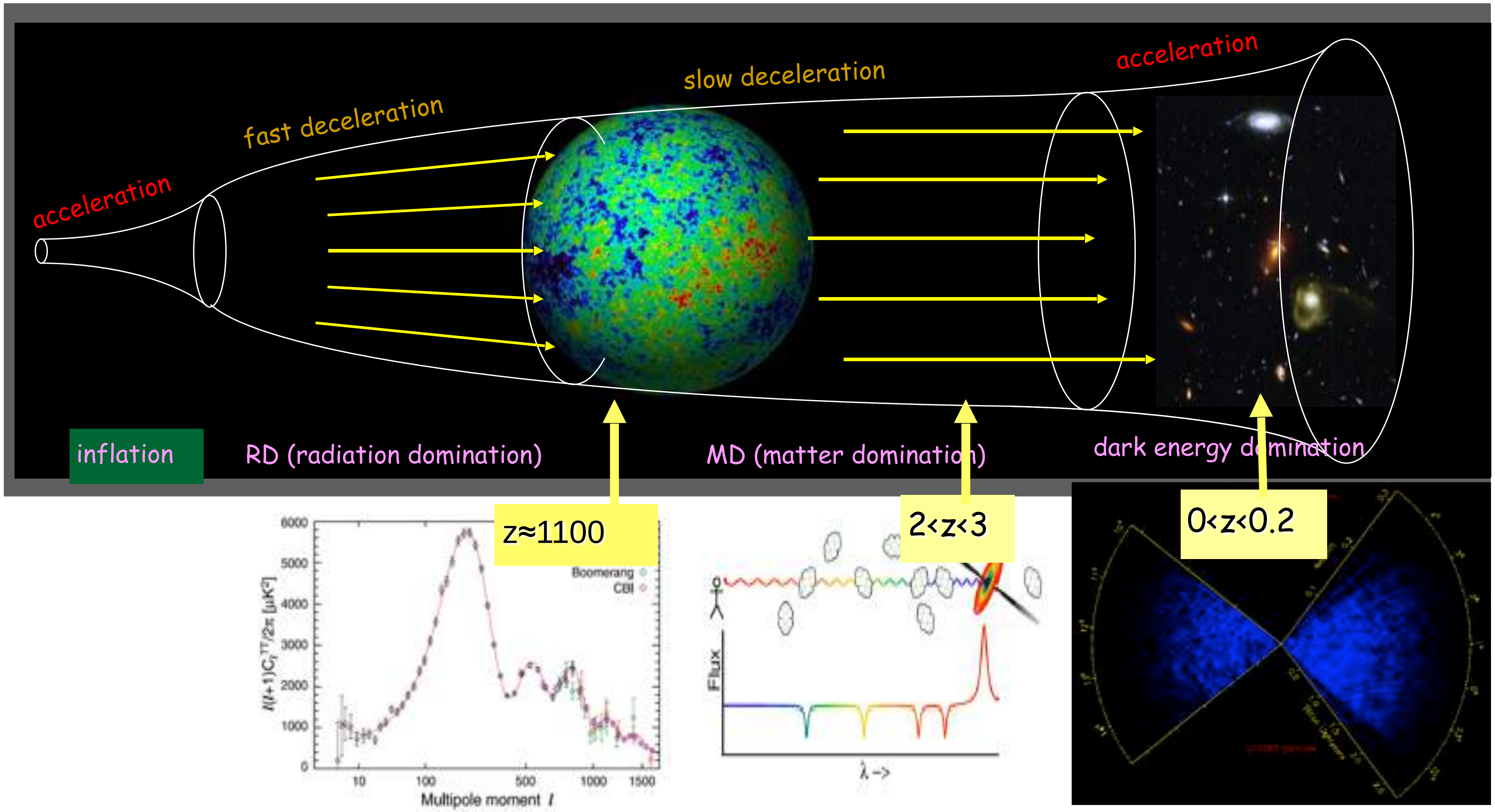
- Over the next decade, a number of proposals/projects from both disciplines will aim to test the mass scale further to the very limits of the predictions from oscillation results → sub eV scale.

- After the discovery of a finite neutrino mass, presently the main research theme is: "We need to imagine and run a sub eV PRECISION EXPERIMENT "

- I will focus this talk on the direct experimental approach: this is a not exhaustive seminar, apologize if many arguments are skipped.

Cosmological constraints (overview)

Imprint of cosmological neutrinos upon the structure evolution of the universe is testable by Cosmology observations



CMB temperature/polarization anisotropies

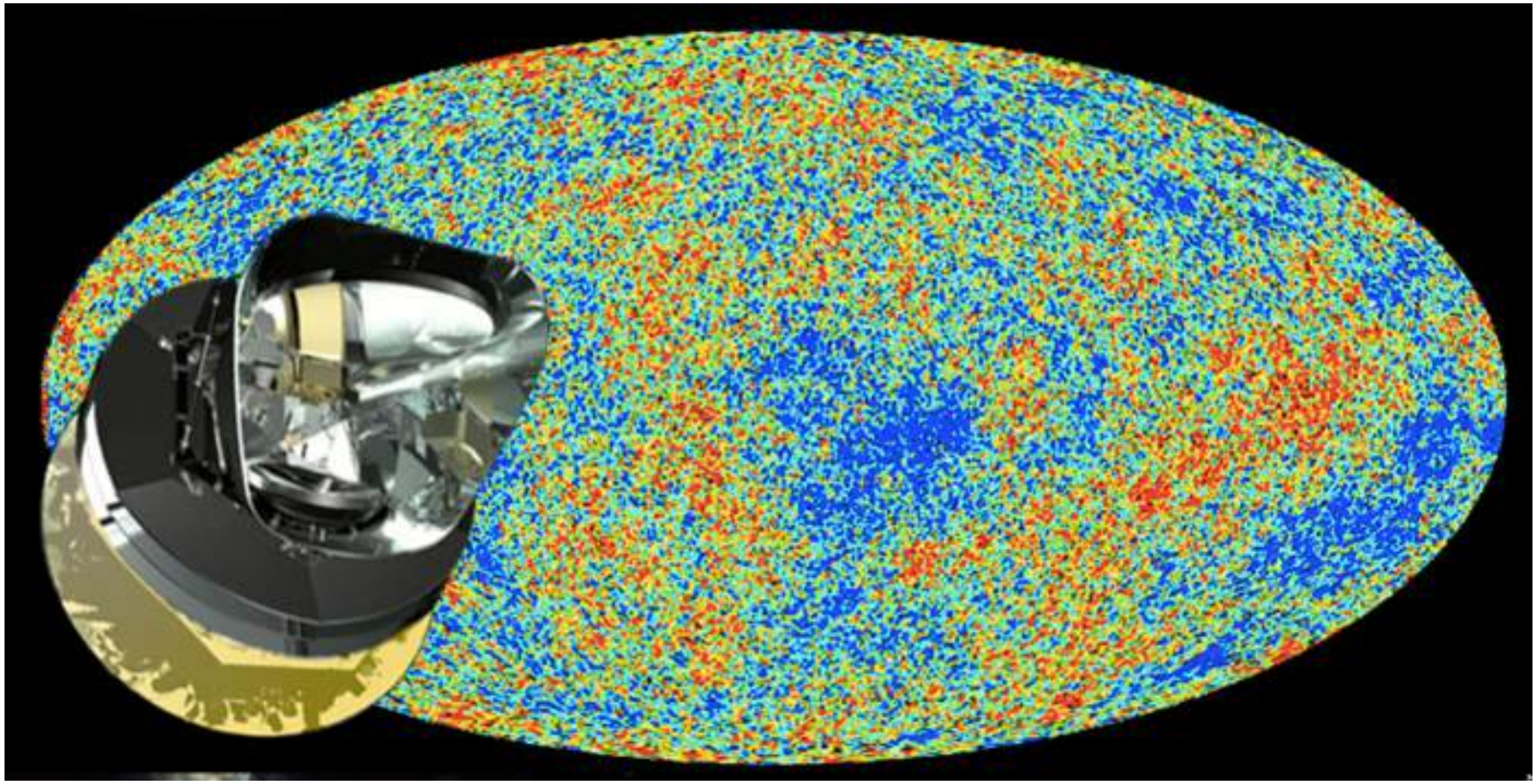
Lyman-α forests in quasar spectra

galaxy redshift surveys

What is the a neutrino for Cosmology

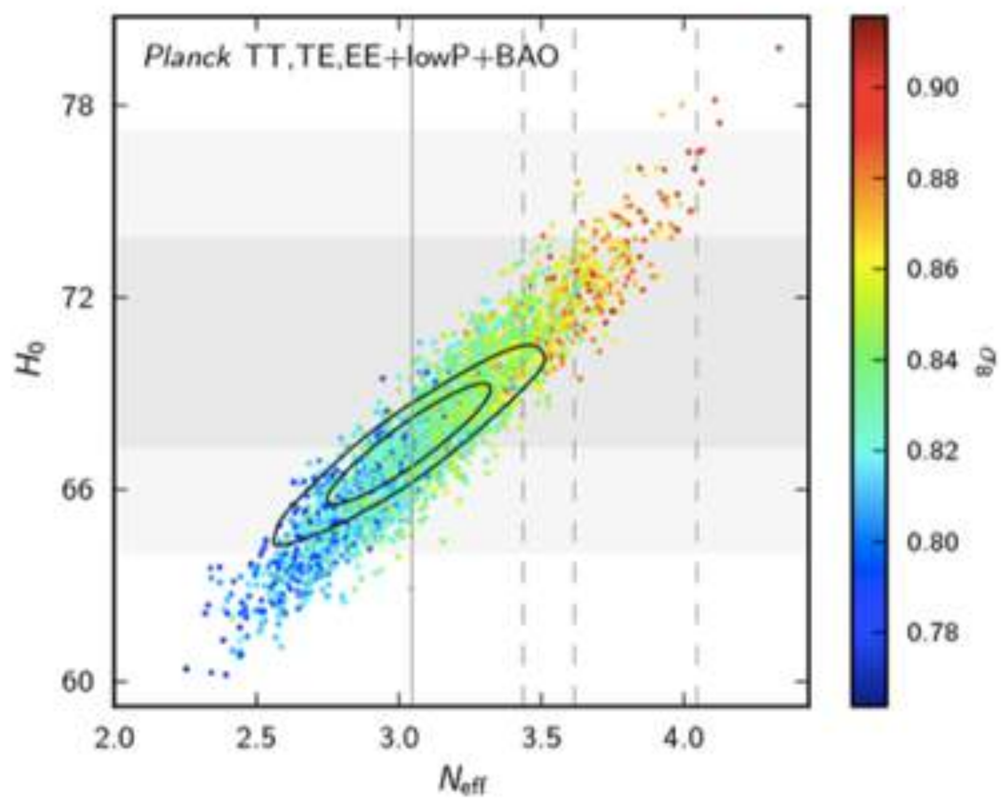
- Behaves like radiation at T~eV
- Eventually(possibly)becomes non-relativistic, behaves like matter
- Small interactions (not perfect fluid)
- Has a high velocity dispersion(is"HOT")

Latest Cosmological Constraints: Plank



Latest Cosmological Constraints: Plank

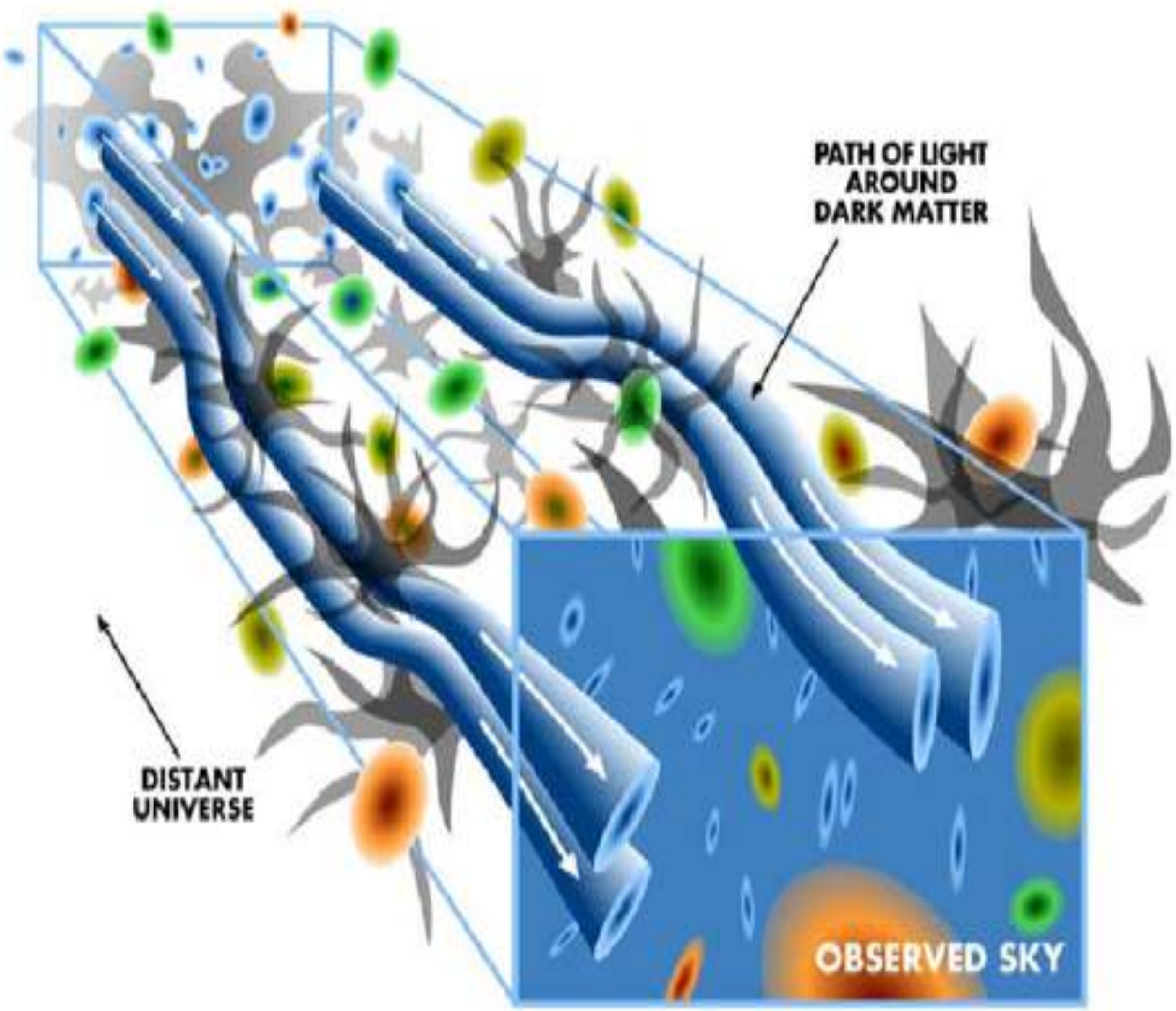
Parameter	TT	TT+lensing	TT+lensing+ext	TT, TE, EE	TT, TE, EE+lensing	TT, TE, EE+lensing+ext
Ω_K	$-0.052^{+0.049}_{-0.055}$	$-0.005^{+0.016}_{-0.017}$	$-0.0001^{+0.0054}_{-0.0052}$	$-0.040^{+0.038}_{-0.041}$	$-0.004^{+0.015}_{-0.015}$	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV]	< 0.715	< 0.675	< 0.234	< 0.492	< 0.589	< 0.194
$N_{\rm eff}$	$3.13^{+0.64}_{-0.63}$	$3.13^{+0.62}_{-0.61}$	$3.15^{+0.41}_{-0.40}$	$2.99^{+0.41}_{-0.39}$	$2.94^{+0.38}_{-0.38}$	$3.04^{+0.33}_{-0.33}$
$Y_{\rm P}$	$0.252^{+0.041}_{-0.042}$	$0.251^{+0.040}_{-0.039}$	$0.251^{+0.035}_{-0.036}$	$0.250^{+0.026}_{-0.027}$	$0.247^{+0.026}_{-0.027}$	$0.249^{+0.025}_{-0.026}$
$dn_s/d\ln k$	$-0.008^{+0.016}_{-0.016}$	$-0.003^{+0.015}_{-0.015}$	$-0.003^{+0.015}_{-0.014}$	$-0.006^{+0.014}_{-0.014}$	$-0.002^{+0.013}_{-0.013}$	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.103	< 0.114	< 0.114	< 0.0987	< 0.112	< 0.113
w	$-1.54^{+0.62}_{-0.50}$	$-1.41^{+0.64}_{-0.56}$	$-1.006^{+0.085}_{-0.091}$	$-1.55^{+0.58}_{-0.48}$	$-1.42^{+0.62}_{-0.56}$	$-1.019^{+0.075}_{-0.080}$



Next Possible Cosmological Constraints

- Lensing of the CMB signal
  Makes CMB sensitive to smaller
  neutrino masses

- $\sigma(m_\nu) \rightarrow 0.01$ eV with CMB
  polarisation missions.



My considerations about Cosmological Constraints

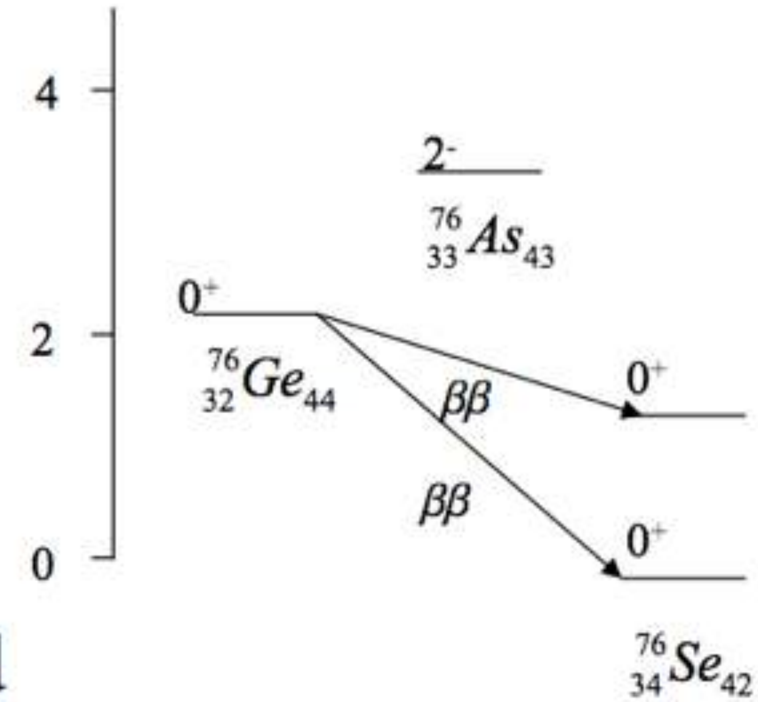
- The neutrino mass limits tend to vary depending on the data used and the exact model employed.
- Some tension between data sets exists.
- Possible mixing of not fully independent data (correlation well estimated?)
- Next generation of CMB missions aim to push well down into the inverted hierarchy region
- But systematic uncertainties and small order corrections will become increasingly important
- → DIRECT SEARCHES IN LABORATORY ARE NEEDED

Laboratory Direct Methods

Double beta decay

A tricky question arose this year. Let start with 0ν decay

$$ {}^{A}_{Z}X_{N} \rightarrow {}^{\;\;A}_{Z\pm2}Y_{N\mp2} + 2e^{\mp} + anything $$



Half-life for processes not allowed by the standard model:

$$ \boxed{\left[\tau_{1/2}^{0\nu\beta\beta}(0^+ \rightarrow 0^+)\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \left|f(m_i, U_{ei})\right|^2} $$

Beyond the standard model
(Particle physics)

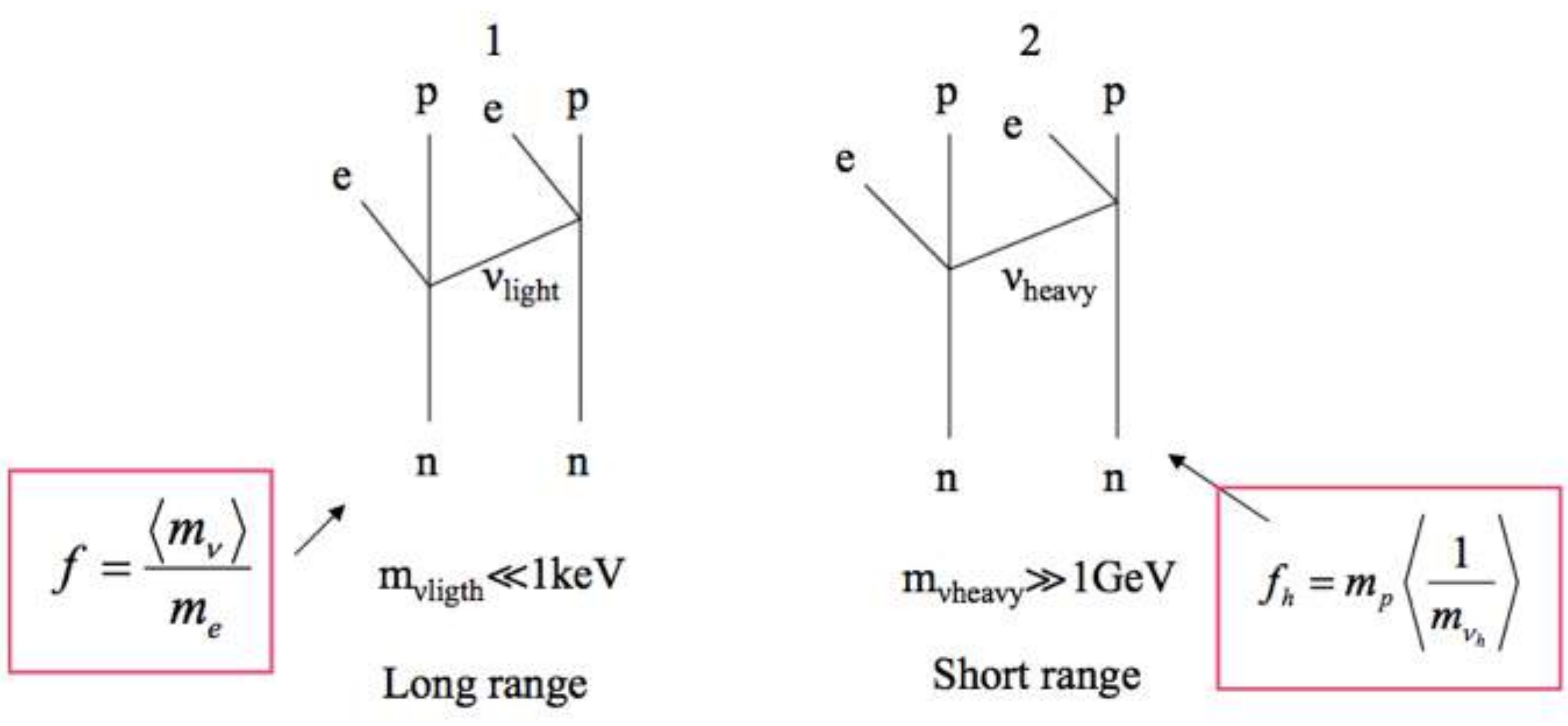
Phase-space factor
(Atomic physics)
PSF

Matrix elements
(Nuclear physics)
NME

F. Iachiello, Yale

Double beta decay

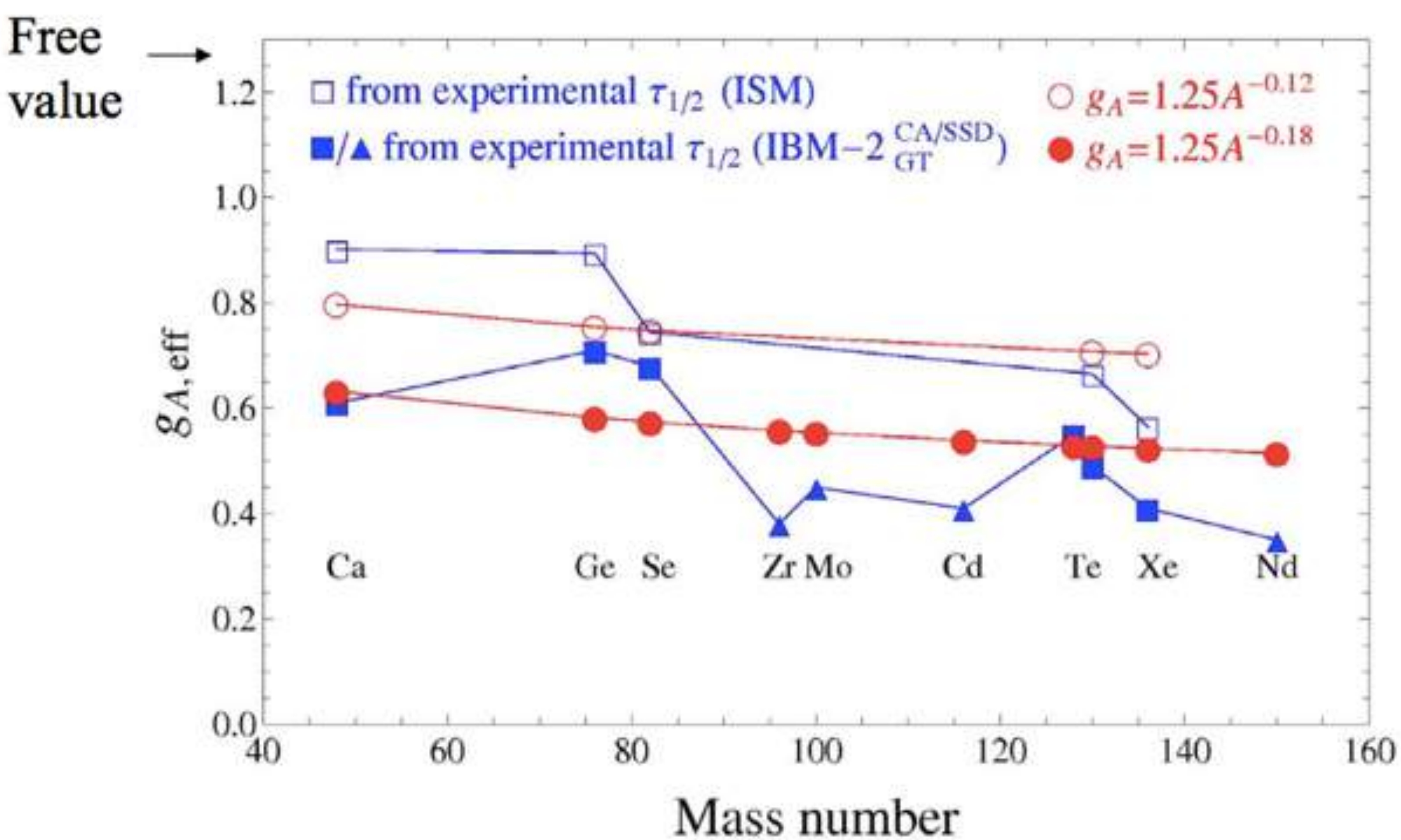
For 0ν processes two scenarios have been considered:
(1) Emission and re-absorption of a light (MeV) neutrino.
(2)Emission and re-absorption of a heavy (GeV) neutrino.



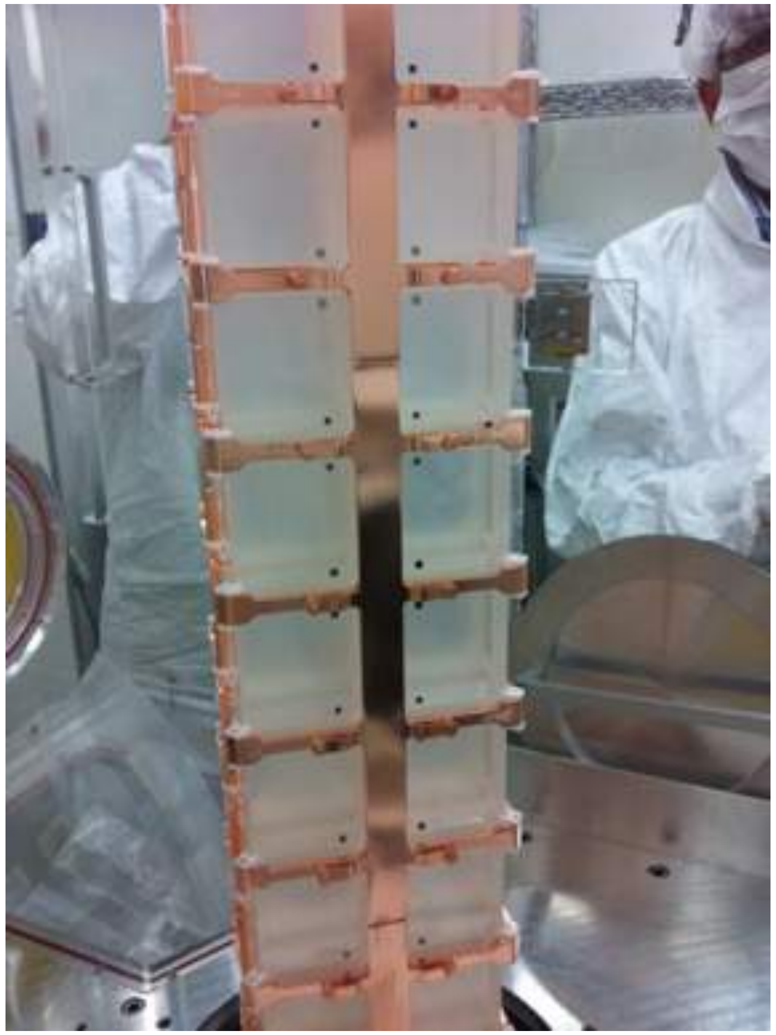
F. Iachiello, Yale

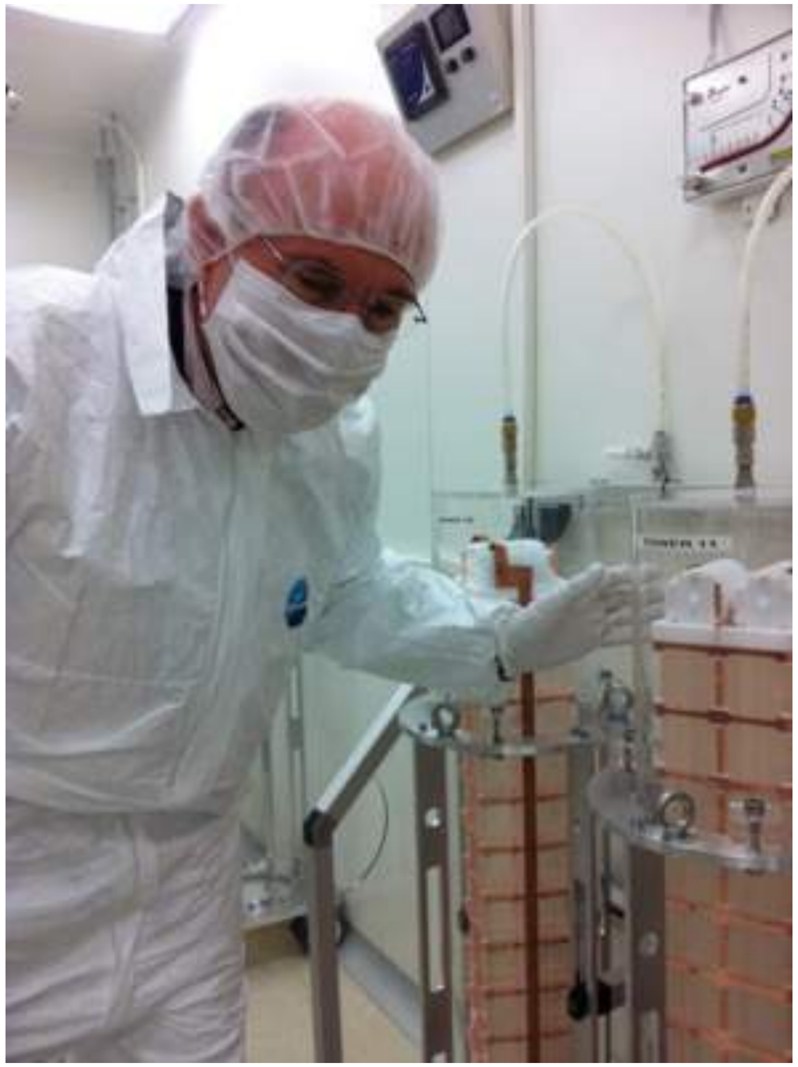
Double beta decay

- The data compilation suggest the effective factor g_A in the nuclear matrix element is lower than one fixed in almost all calculations (g_A =1.269)
- This has been seen on 0ν 2β decay and the half life goes like g_A^4
- The physics of 2ν 2β decay is not exactly the same and this effect can be negligible on the present experiments but the investigations are under way.



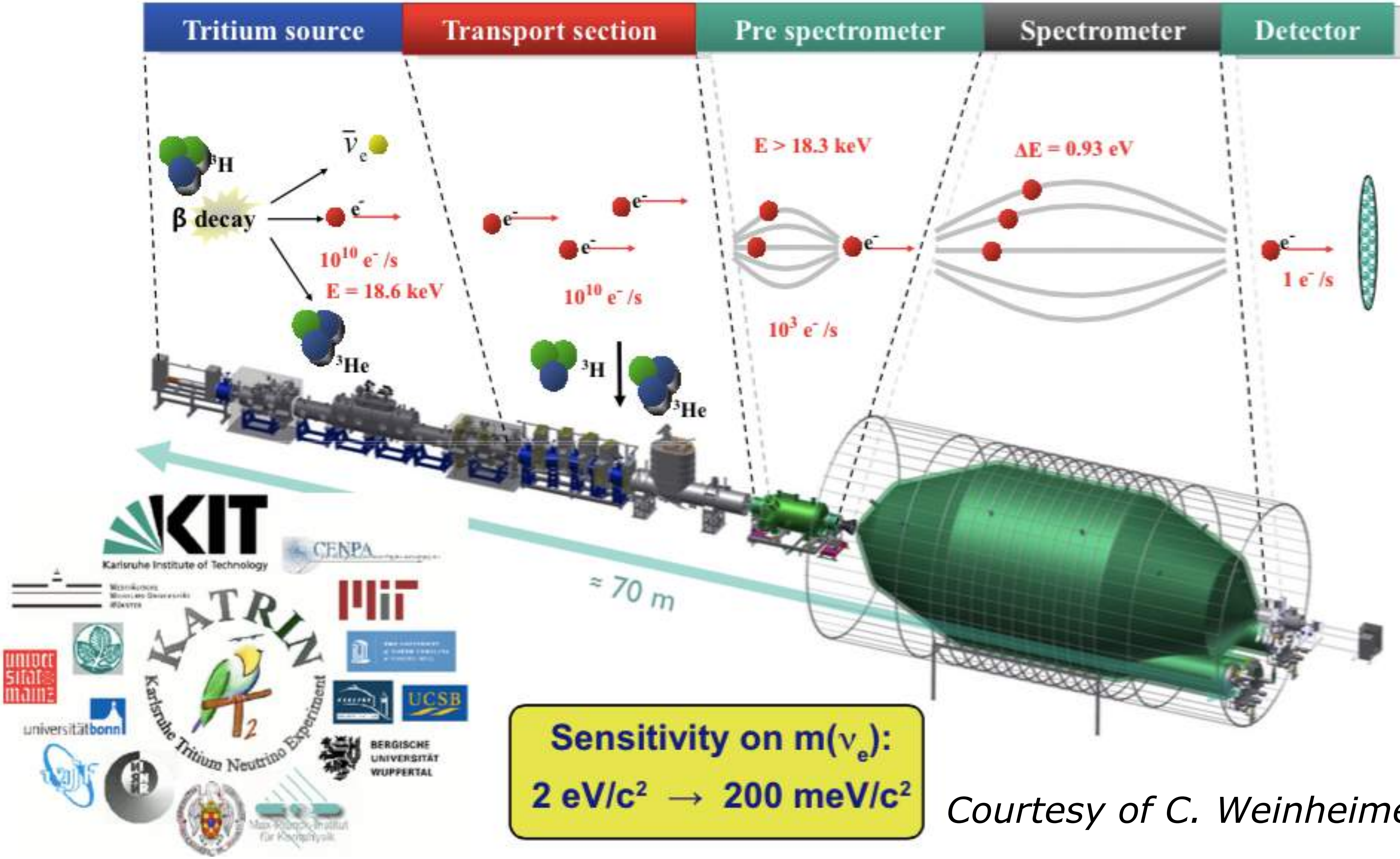
CUORE: one of the major achievements in LTD large experiments





Masiero (Theoretician) , INFM Management vist CUORE

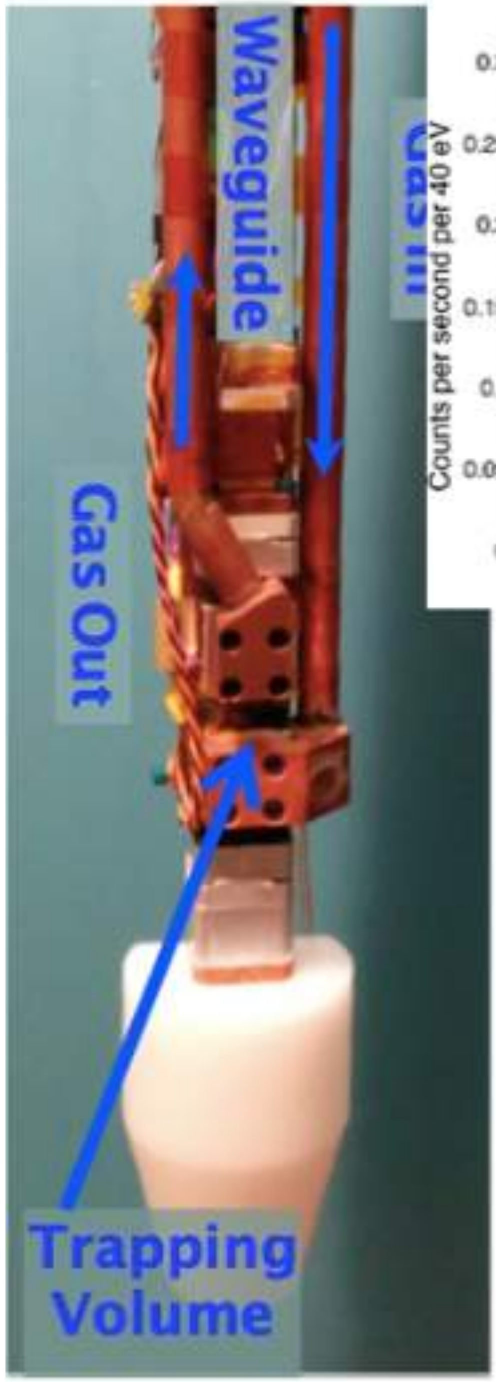
Katrin

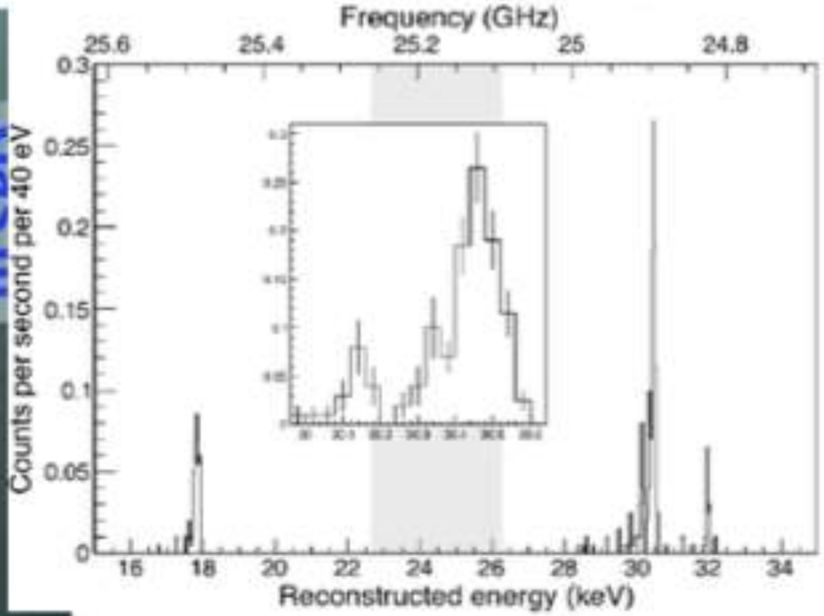


Sensitivity on $m(\nu_e)$:
$2\ eV/c^2 \rightarrow 200\ meV/c^2$

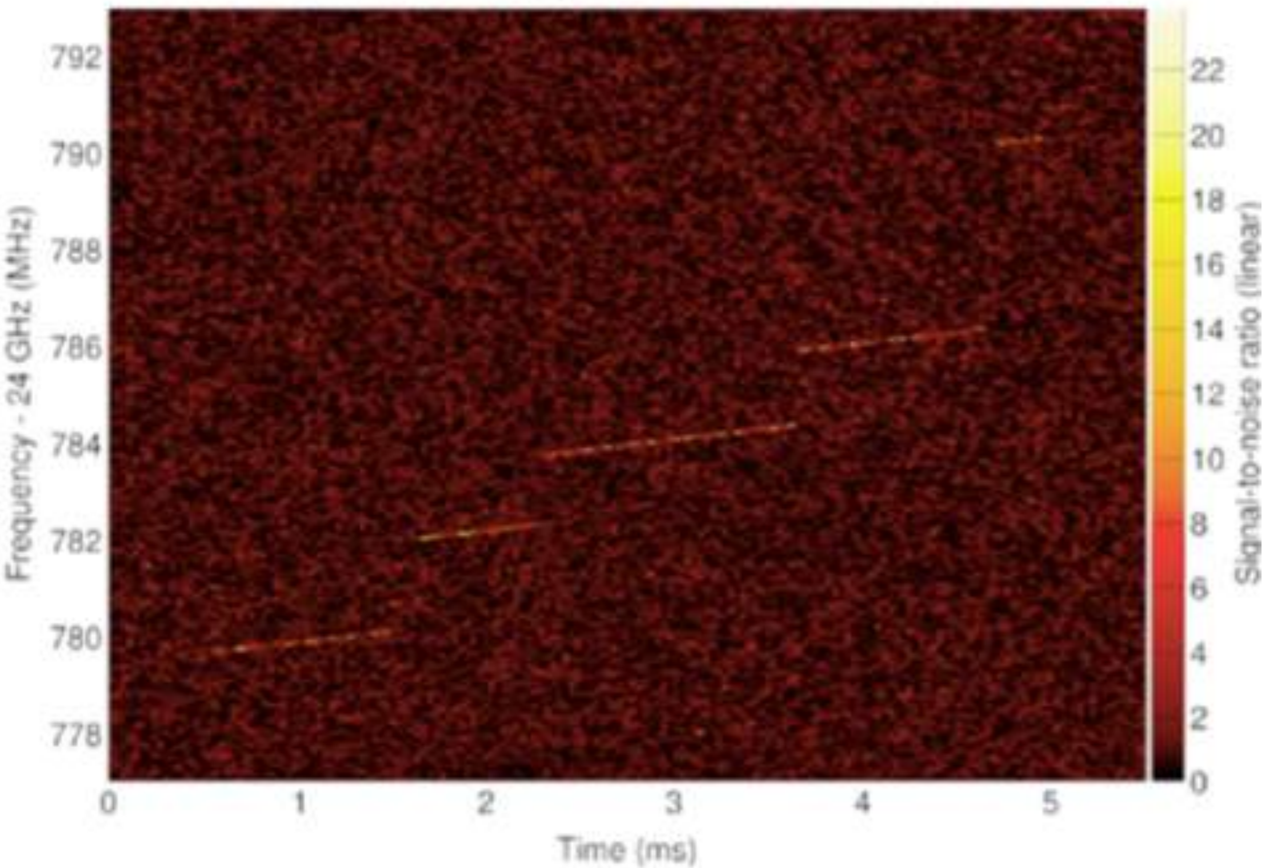
Courtesy of C. Weinheimer

Project8



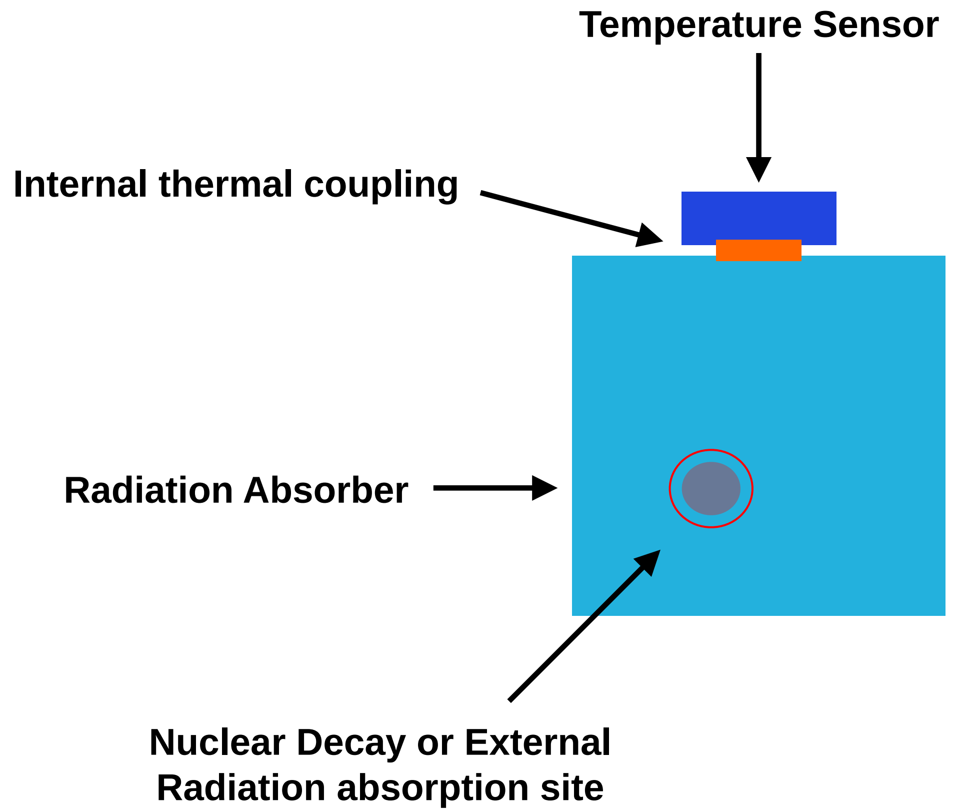


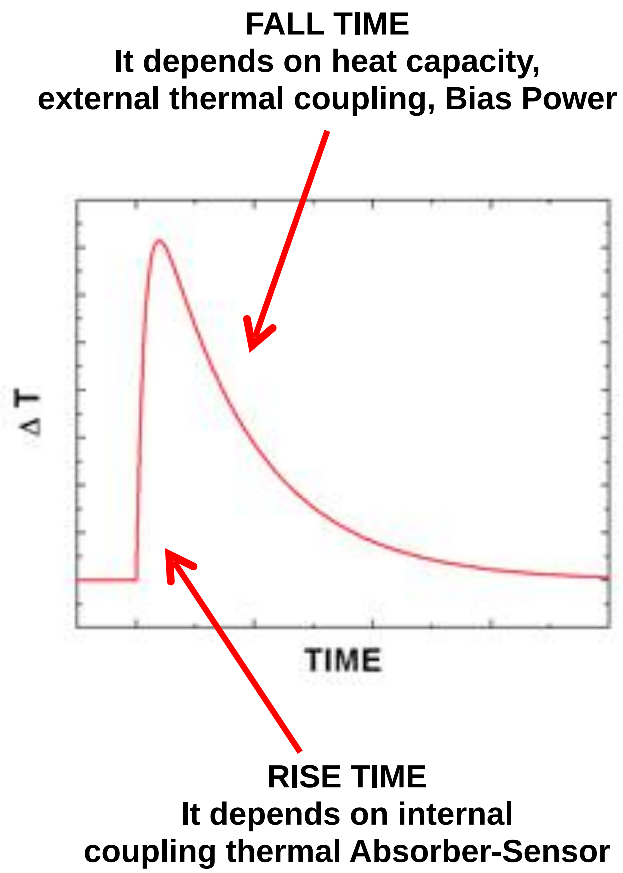
D. M. Asner et al., arXiv:1408.5362



Courtesy of J. Formaggio

Mass measurement with cryogenic μ-calorimeter



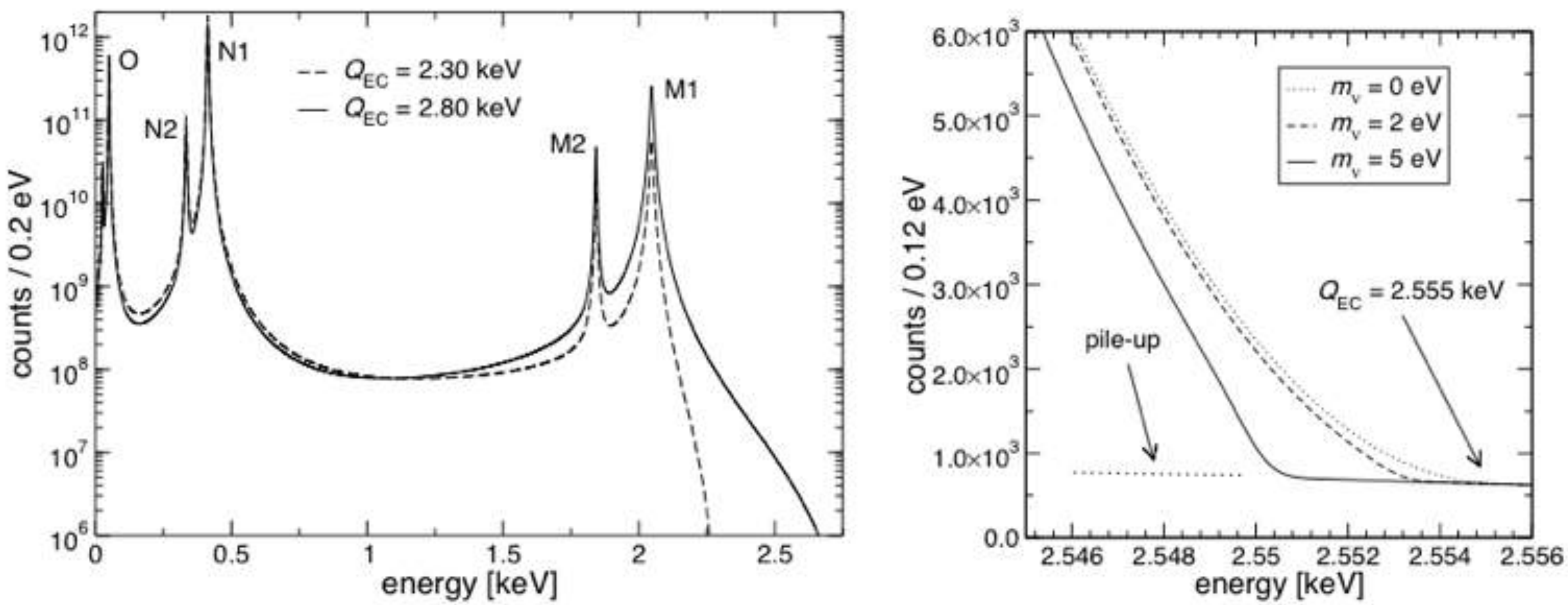


- It's ideally an Energy Dispersive Spectroscopical Detector
- It's a fast (0.1-1 μs) true thermal calorimeter
- Energy Sensitivity at the eV scale needs very low heat capacity at the scale less than pJ/K
- The Energy Resolution Intrinsic is ultimately limited by the thermal fluctuation noise:
- Sub-K operating temperatures are needed (0.01-0.1 K) to reach eV resolutions
- IN PRINCIPLE THEY ARE A TOOL FOR VERY DEEP SEARCHES IN SUB-eV range

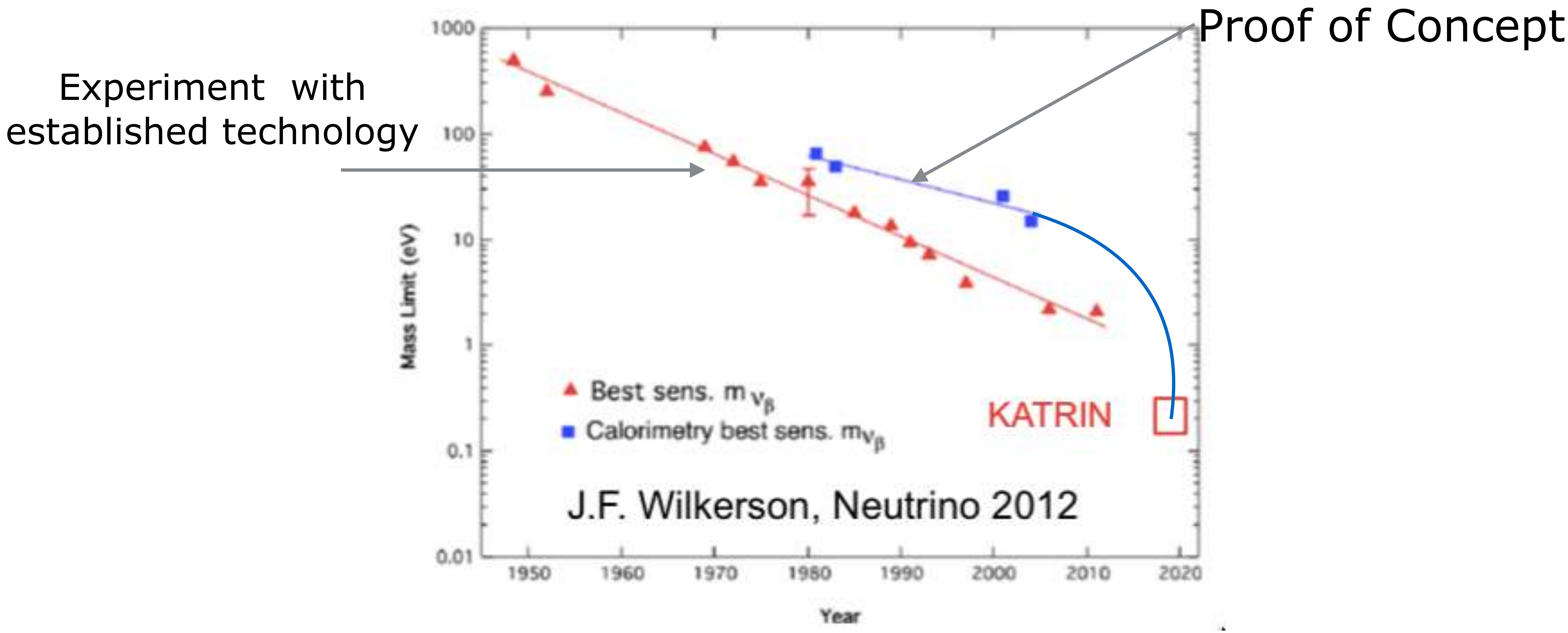
Mass measurement with cryogenic μ-calorimeter

$^{163}Ho + e^{-} \rightarrow {}^{163}Dy^{*} + \nu_e$ electron capture decay

(A. De Rujula and M.Lusignoli, Phys. Lett. 9 (1982)



Conclusions on direct mass searches



- KATRIN was the only proposal based on proved technology
- MARE was proposed as very ambitious project later after the R&D of MANU and MIbeta projects
- Now HOLMES, ECHo, NuMEX(LANL) point to a realistic goal in the sub eV range
- Project8 is a very promising technique beyond KATRIN

General Conclusion

- Neutrino properties can be successfully investigated with LTDs, but experiments are becoming more and more complex and large
- In most cases LTDs are unique tools and more young researchers should join the community.