Application of cryogenic detectors in subnuclear and astroparticle physics

Angelo Nucciotti
Dipartimento di Fisica "G. Occhialini"
Università di Milano-Bicocca
and INFN Sezione di Milano

LTD
11
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Takeda Hall, University of Tokyo, JAPAN
August 1st, 2005

Outline

- **subnuclear physics: i.e. neutrino physics**
  - heaviest neutrino mass $m_{2,3} \geq \sqrt{(\Delta m^2_{\mathrm{atm}})} \approx 0.05$ eV
  - **still missing:**
    - mass scale (i.e. lightest neutrino mass)
    - hierarchy ($m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 \approx m_2$) or degeneracy($m_1 \approx m_2 \approx m_3$)?
    - Dirac or Majorana particle? ...
  - **direct neutrino mass measurement (β decay)**
  - **neutrinoless double beta decay ($\beta\beta$-0ν) searches**
- **astroparticle physics: i.e. non-baryonic dark matter**
  - universe is flat: Ω**=1**
  - Λ-CDM model: 1/3 of the universe is ***matter, largely non-baryonic***
  - **still missing:**
    - exact matter composition
    - what is the non-baryonic matter? ...
  - **cold dark matter direct searches**

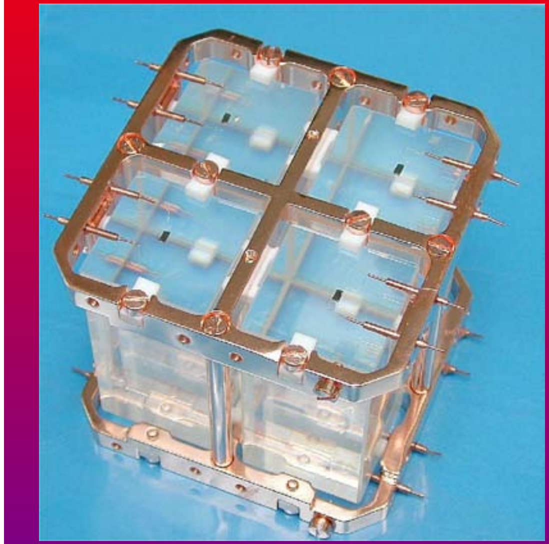
- many exciting news in the last years!
  - cryogenic detectors are doing the right physics at the right time!
- role of present and next generation cryogenic detector experiments

Why cryogenic detectors?

Many years of R&D because of several pros and few cons:

- ▲ true calorimeters
- ▲ fully sensitive to recoils
- ▲ wide material/nuclei choice:
  - Si, Ge, Re, Al_2O_3, TeO_2, $CaWO_4$, LiF, BGO, $CdWO_4$, $PbMoO_4$, CaF_2, $AgReO_4$, ...
- ▲ high energy resolution, low threshold
- ▲ large masses
- ▲ segmentation to reduce background
- ▼ fully sensitive to surface radioactivity
- ▼ difficult to reduce close materials (holders, wires, cryostats,...)
- ▼ not easy to run stable
- ■ hybrid detectors can do particle identification (i.e. e/γ - recoil, e/γ - α):
  - heat + scintillation detection
  - heat + ionization detection
- ■ can be position sensitive: timing, PSD+segmentation

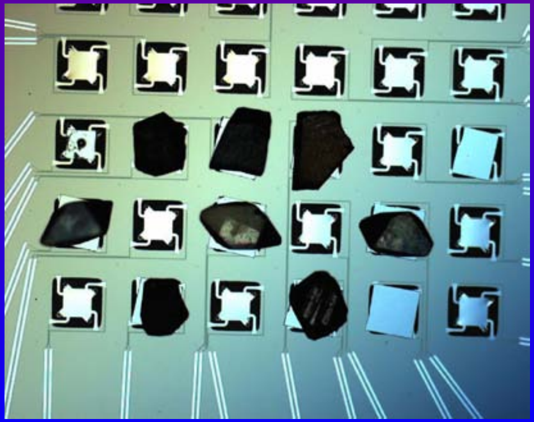
Cold DM and $\beta\beta$-0ν searches



kg – ton

keV – MeV

Direct neutrino mass measurements



mg – g

keV

Cryogenic detectors: from prototypes to next generation

'90s TeO_2, Ge, Si, Al_2O_3, Re, $AgReO_4$,...

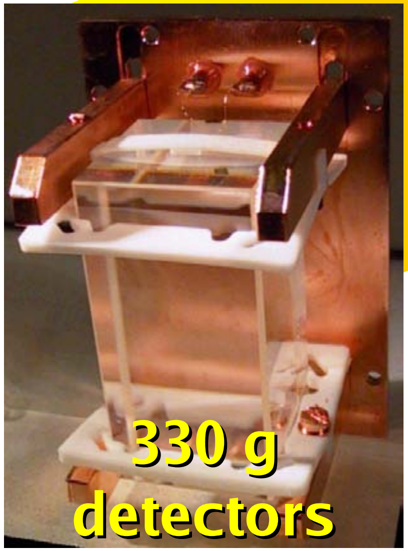
⇒ lot of R&D on these exotic detectors...

2000 CDMS, Edelweiss, Cresst, MANU, MIBETA (TeO_2, $AgReO_4$),...

⇒ first important physics result!

today present generation experiment: Cuoricino, CRESST-II, CDMS-II, Edelweiss-II, MARE-I (MANU2...)

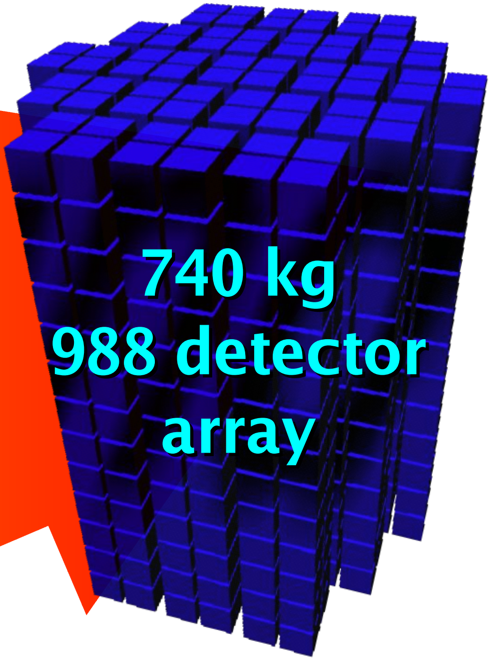
cyogenic detectors has become “normal”!



330 g detectors

7 kg 20 detector array

41 kg 62 detector array



740 kg 988 detector array

2010-15

next generation

i.e. ***the brute-force***

CUORE

SuperCDMS

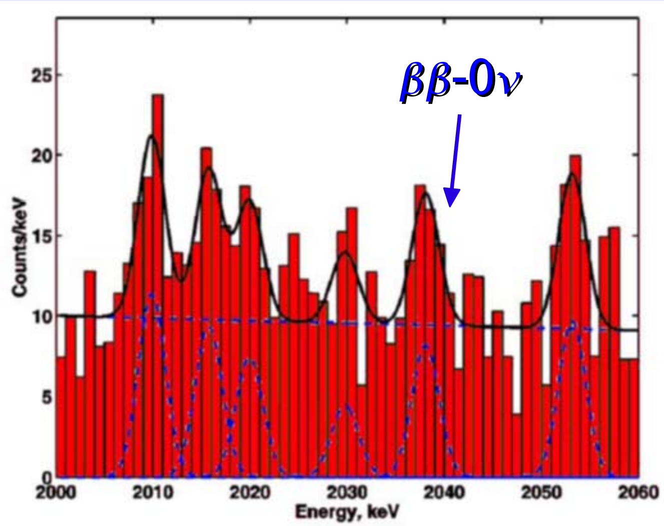
MARE-II

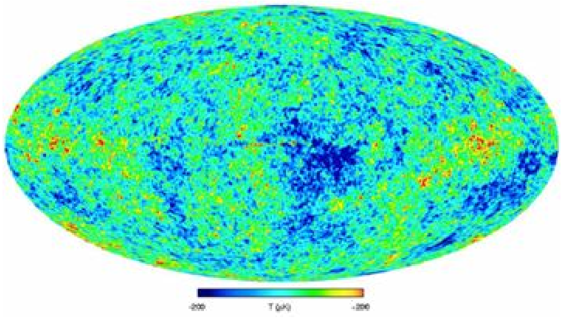
...

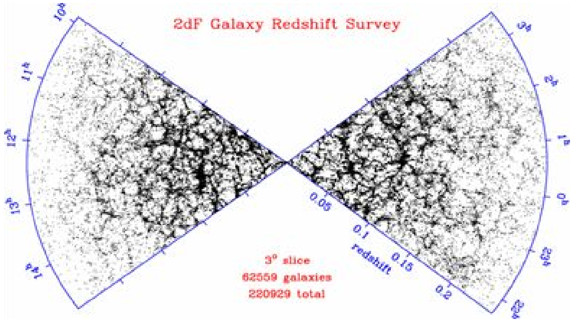
high discovery potential

Indirect neutrino mass measurement

- **Neutrinoless Double Beta Decay** $(A, Z) \rightarrow (A, Z+2) + 2e^-$
  - ▷ requires Majorana neutrinos: $\nu \equiv \overline{\nu}$
  - ▷ measures effective neutrino mass: $\langle m_\nu \rangle = |\sum_k m_{\nu k} \eta_k |U_{ek}|^2|$
  - ▷ controversial evidence for $\beta\beta$-0ν of ^{76}Ge in the Heidelberg-Moscow experiment
    - ▶ $\langle m_\nu \rangle = 0.1 \div 0.9$ eV
  - ▷ Cuoricino, CUORE or GERDA will check this claim in the next years







- **Cosmological bounds**
  - ▷ Cosmic Microwave Background (WMAP,...)
  - ▷ Large scale structure surveys (2dFGRS, Lyα,...)
    - ▶ $\sum m_i \leq 0.7 \div 2$ eV
    - ▶ extremely model dependent

Present ββ-0ν experimental situation

- **best result** per isotope to date
- exposure: **exp = $M \times t_{meas}$**

🟧 positive result

🟩 running experiments

$$\sum \left(\tau^{0\nu}_{1/2}\right) \propto \epsilon \cdot \frac{i.a.}{A}\sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}}$$

isotope	**experiment**	**latest result**	**$Q_{\beta\beta}$** [keV]	**i.a.** [%]	**enrich** [%]	**exp** [kg×y]	**tech**	**material**	$\tau_{1/2}^{0\nu}$ [10^{23} y]	$\langle m_\nu \rangle$ [eV] min	max	$\tau_{1/2}^{0\nu}\vert_{10meV}$ [10^{28} y] max
^{48}Ca	Elegant VI	2004	4271	0.19	-	4.2	s	CaF_2	0.14	7.20	44.70	8.8
^{76}Ge	Heidelberg/Moscow	2001	2039	7.8	87	71.7	i	Ge	🟧 120.0	🟧 *0.44*		17.7
^{82}Se	🟩 NEMO-3	2004	2995	9.2	97	0.55	t	Se	1.9	1.30	3.60	5.6
^{100}Mo	🟩 NEMO-3	2004	3034	9.6	95-99	4.1	t	Mo	3.5	0.70	1.20	3.9
^{116}Cd	Solotvina	2003	3034	7.5	83	0.5	s	$CdWO_4$	1.7	*1.70*		4.7
^{130}Te	🟩 Cuoricino	2005	2533	34.5	-	5	b	TeO_2	18.0	0.21	1.10	5.8
^{136}Xe	🟩 DAMA	2002	2476	8.9	69	6.4	s	Xe	12.0	1.10	2.90	12.1
^{150}Nd	Irvine TPC	1997	3367	5.6	91	0.01	t	Nd_2O_3	0.012	*3.00*		0.1

$$\langle m_\nu\rangle^2 = \frac{1}{F_N}\cdot\frac{m_e^2}{\tau^{0\nu}_{1/2}}$$

$$F_N \equiv G^{0\nu}(Q_{\beta\beta},Z)\,|M^{0\nu}|^2$$

s scintillation
i ionization
t tracking
b bolometric

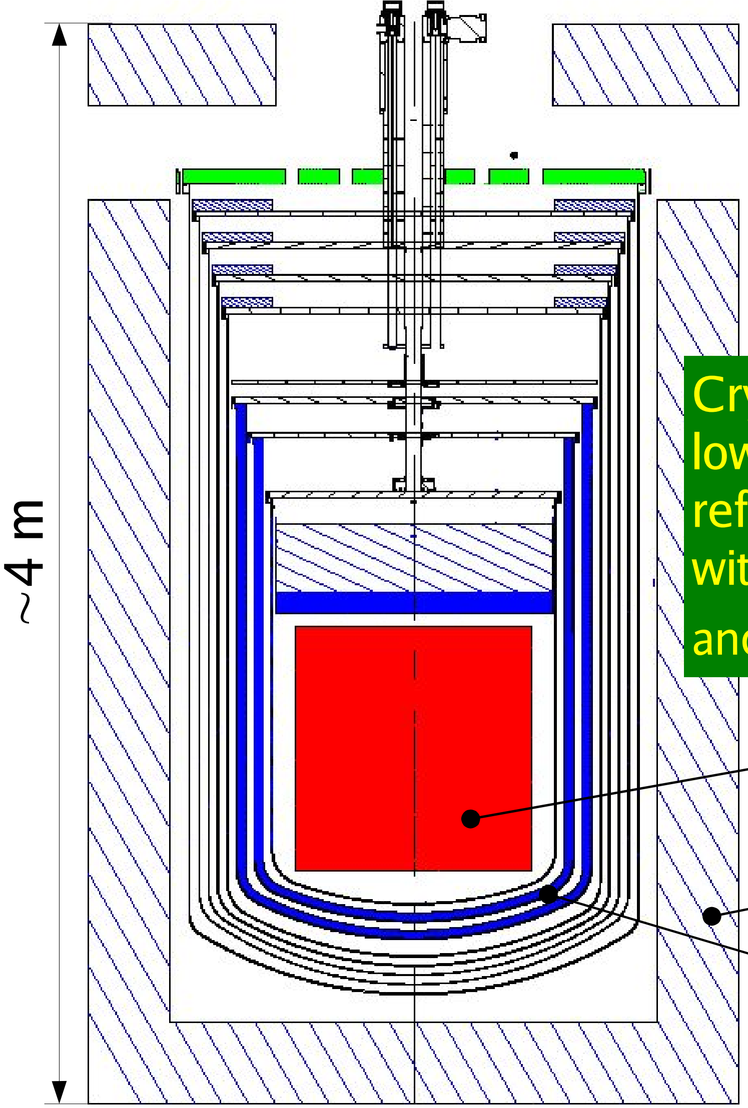
spread due to uncertainties in F_N
i.e. nuclear physics

half-life expected for $\langle m_\nu\rangle$ = 10 meV
and the **less favorable F_N**

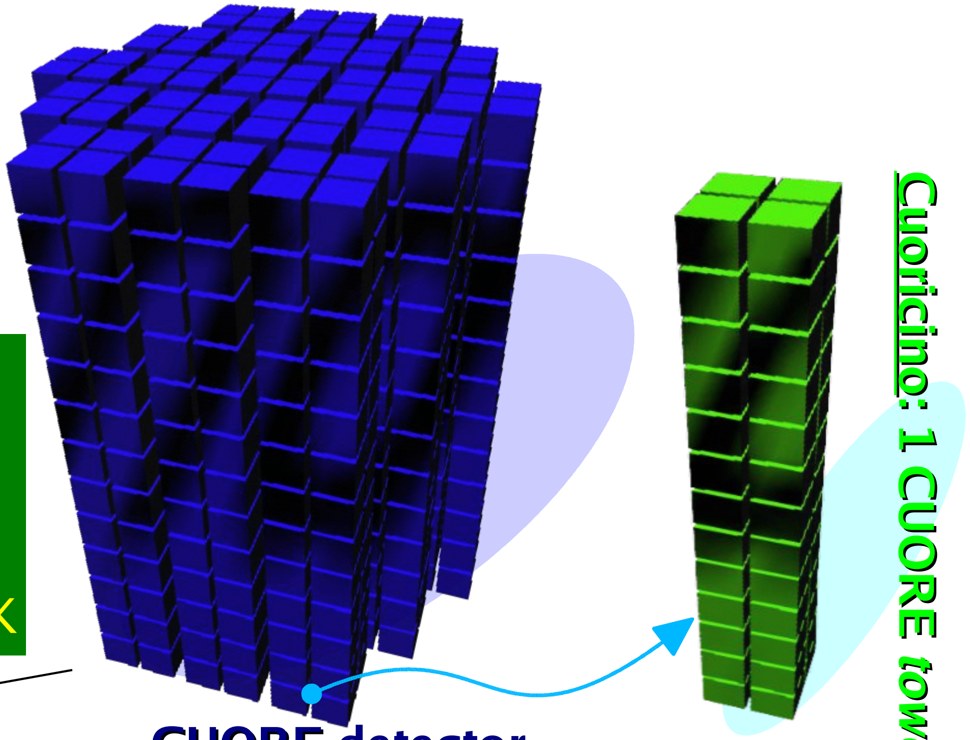
The CUORE experiment

Cryogenic Underground Observatory for Rare Events

- array of 988 TeO_2 crystals 5×5×5 cm^3 (750 g) @ LNGS
  - 740 kg TeO_2 granular calorimeter ⇒ 200 kg of ^{130}Te
- $\beta\beta$-0ν, Cold Dark Matter, Axions searches



Cryogen free and low background refrigerator with T_{base}<6 mK and P>5μW@12mK



CUORE detector
19 *towers* – 52 detectors each

Pb shielding (30 cm)
roman Pb shielding (3+3 cm)
about 10 tons cold Pb shielding

C. Arnaboldi *et al.*,
CUORE: A Cryogenic Underground Observatory for Rare Events,
NIM A 518 (2004) 775

Future $\beta\beta$-0ν experiments

- **most representative proposals per isotope**
- some proposed experiments are still **too generic** to fit in the table (NEMO-4, XMASS, COBRA, Nano-crystals...)
- only the **CUORE** experiment is **fully approved** and is being prepared **full size**
- $\tau_{1/2}^{0\nu}$ sensitivity **strongly depends** on ***bkg*** estimation
- **cost** is only **very indicative**

	isotope	$Q_{\beta\beta}$ [keV]	technique	i.a. [%] *	*M* [kmol]	t_{meas} [y]	σ_E [keV]	*bkg* [c/y] **	$\tau_{1/2}^{0\nu}$ [10^{28} y]	$\langle m_\nu \rangle$ [meV] min	$\langle m_\nu \rangle$ [meV] max	project status	cost
CANDLES IV+	**^{48}Ca**	4271	s	2	0.9	5	73	0.35	*0.30*	29	54	R&D (III: 5 mol)	
Majorana	**^{76}Ge**	2039	i	90	6.6	5	2	1	0.40	21	67	R&D (SEGA)	$$$
GERDA-II	**^{76}Ge**	2039	i	90	0.5	2	2	0.2	0.02	92	297	APPROVED (I: 0.2 kmol)	$$
Genius	**^{76}Ge**	2039	i	90	13.0	10	2	0.4	1.00	13	42	R&D (CTF: 10kg)	$$$
MOON III	**^{100}Mo**	3034	t	85	8.5	10	66	*3.8*	0.17	13	48	R&D (I: small)	
CAMEO III	**^{116}Cd**	3034	s	83	2.7	10	47	4	0.10	22	69	proposed	
CUORE	**^{130}Te**	2533	b	*35*	1.7	10	4	7.5	0.07	15	91	**APPROVED: start in 2010**	$
EXO	**^{136}Xe**	2476	t	65	48.0	10	49	*0.55*	1.30	12	31	R&D (1.5 kmol)	$$
DCBA-II	**^{150}Nd**	3367	t	80	2.7		85		0.01	16	22	R&D (T: small)	
GSO	**^{160}Gd**	1730	s	*22*	2.5	10	83	200	0.02	65		proposed	

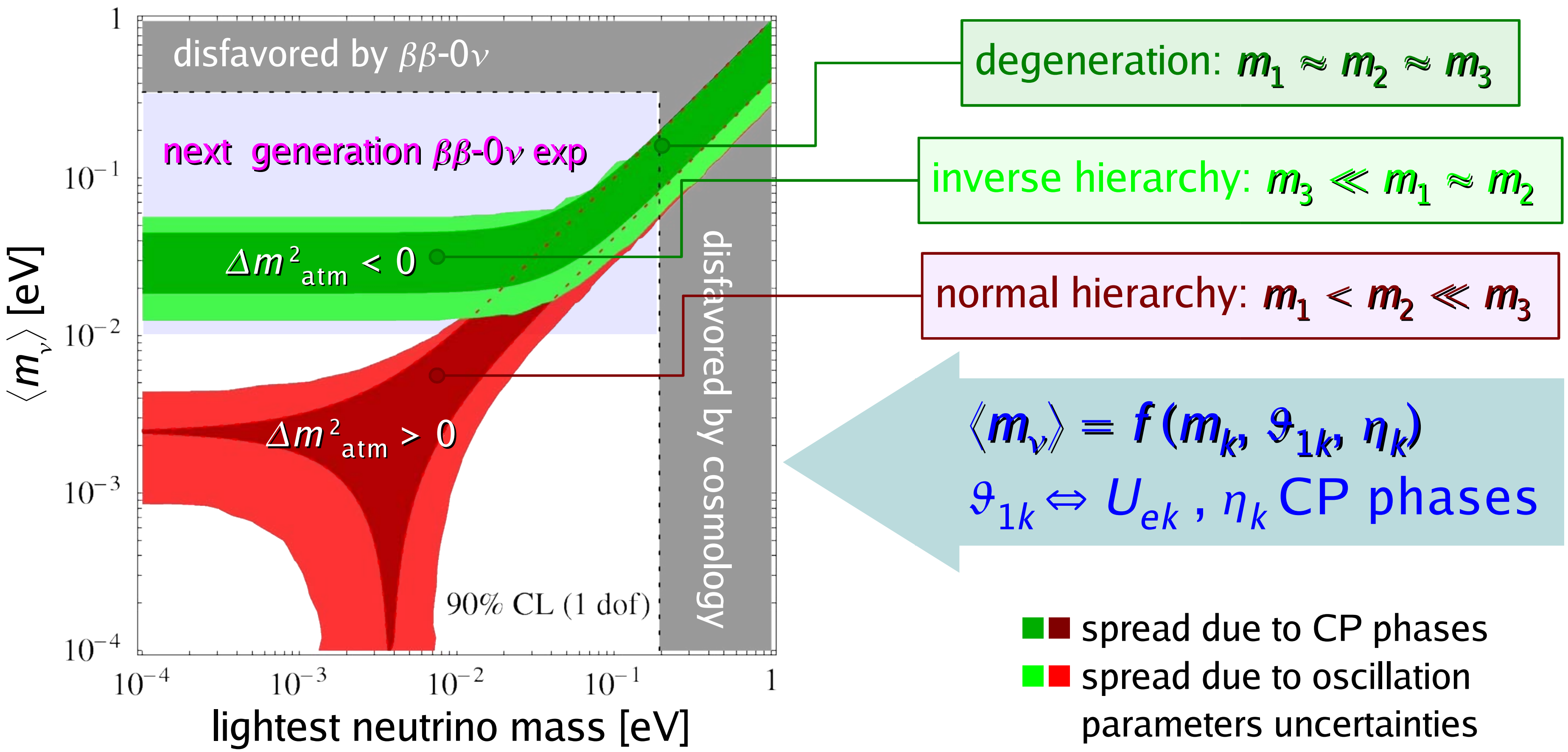
s scintillation
i ionization
t tracking
b bolometric

* 🟦 natural isotopic abundance (i.e. no enrichment required)

** ⬜ only $\beta\beta$-2ν background considered

Role of ββ-0ν in future neutrino physics

- next generation experiments aim at $\langle m_\nu \rangle \approx 10$ meV



degeneration: $m_1 \approx m_2 \approx m_3$

inverse hierarchy: $m_3 \ll m_1 \approx m_2$

normal hierarchy: $m_1 < m_2 \ll m_3$

$\langle m_\nu \rangle = f(m_k, \vartheta_{1k}, \eta_k)$

$\vartheta_{1k} \Leftrightarrow U_{ek}$, η_k CP phases

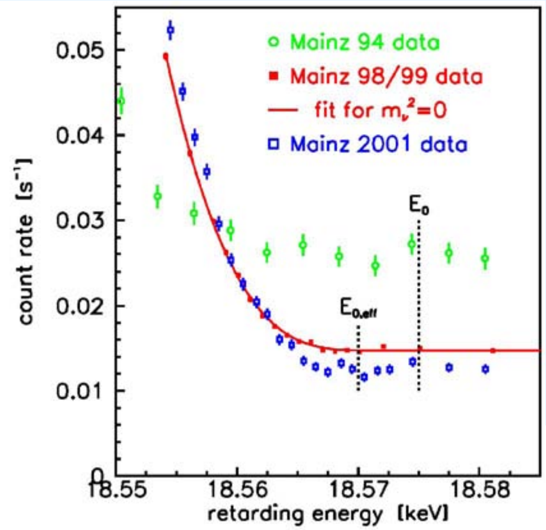
🟩🟥 spread due to CP phases

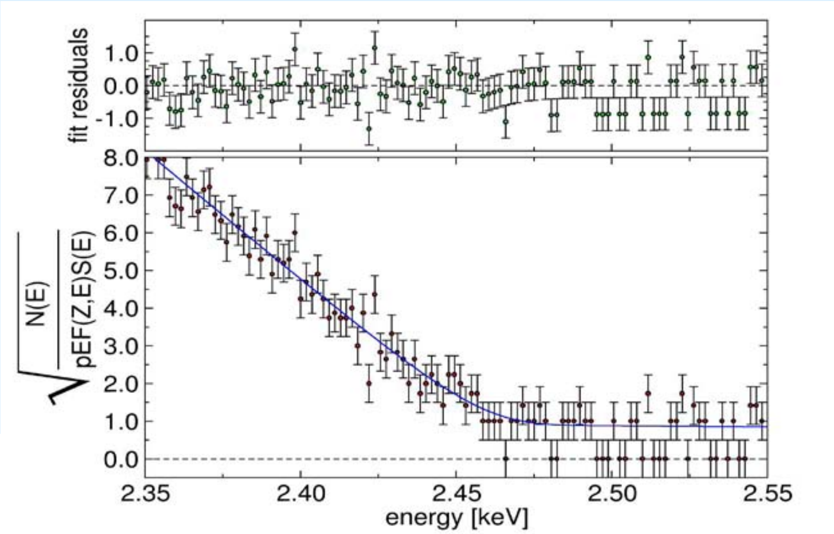
🟩🟥 spread due to oscillation parameters uncertainties

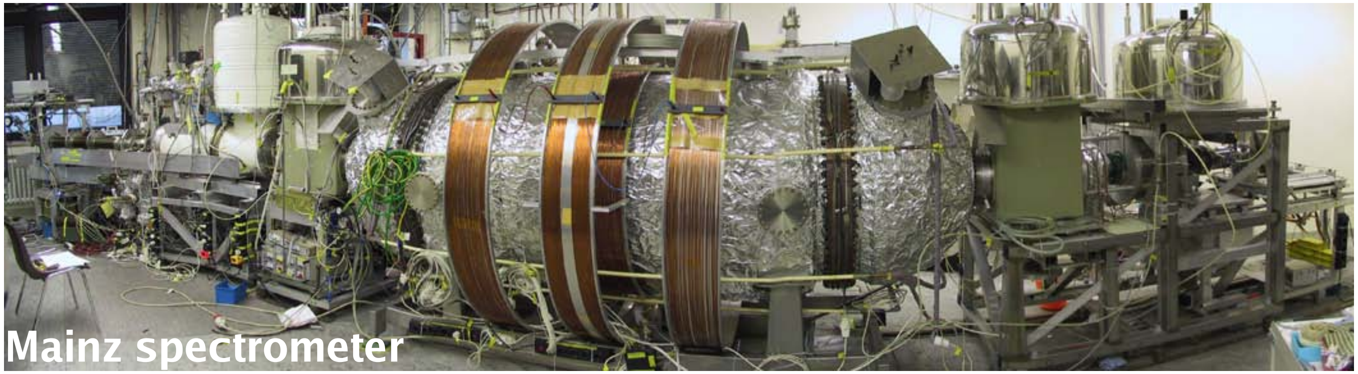
- discovery with $\langle m_\nu \rangle \geqslant 10$ meV
  - the neutrino is a **Majorana particle**
  - **inverse hierarchy** or **degeneration**
  - **absolute ν mass scale** fixed in case of degeneration
- upper limit with $\langle m_\nu \rangle < 10$ meV
  - normal hierarchy (only with Majorana neutrinos)

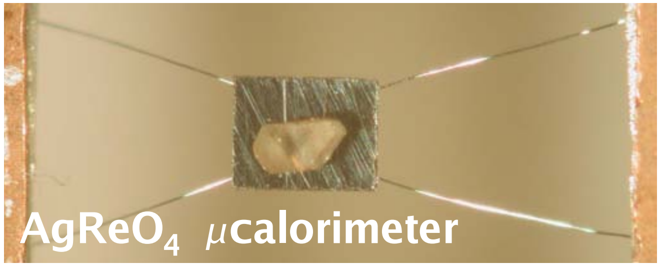
Direct neutrino mass measurement

- **Weak decay kinematics:** study of decays with neutrinos in the final state
  - β decay end-point study ⇒ **free of theoretical assumption**
  - **^{3}H β decay with electrostatic spectrometers:**
    $^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$ → $m_{\nu_e} \leqslant 2.1$ eV/c^2 at 95% C.L. (Mainz, Troitzk)
  - **^{187}Re β decay with thermal calorimeters:**
    $^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^- + \bar{\nu}_e$ → $m_{\nu_e} \leqslant 15$ eV/c^2 at 90% C.L. (MANU, MIBETA)






Mainz spectrometer


AgReO$_4$ μcalorimeter

Future neutrino mass experiments: the MARE project

an international collaboration for a new project

MARE: Microcalorimeters Array for Rhenium Experiments

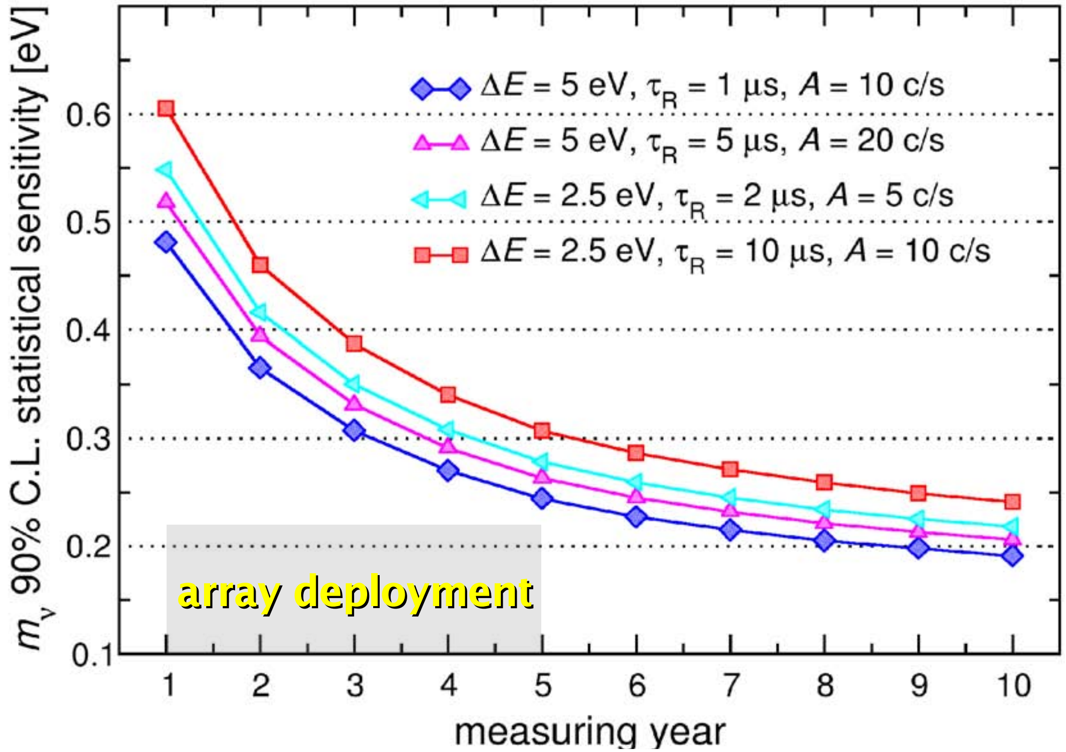
Università di Genova e INFN-Genova, Kirchhoff Institut-Universität Heidelberg,
Università dell'Insubria, Università di Milano-Bicocca, INFN-Milano,
NASA Goddard Space Flight Center, ITC-irst/Trento, Wisconsin University- Madison

- goal: **calorimetric experiment with 0.1÷0.2 eV m_ν sensitivity**
  - systematics different from KATRIN spectrometer experiment
- **phase I:** 2006 - 2009
  - 2 new experiments with TES (MANU2) and thermistor (MIBETA2) arrays
    - confirm present spectrometer results around 2 eV
    - check for unexpected sources of systematics at 1 eV level (BEFS?)
- **phase II:** 2010 - ...
  - **m_ν statistical sensitivity better than 0.2 eV** (≈KATRIN experiment)
  - 10^{14} events with $\Delta E \leqslant 5$eV and $\tau \leqslant 5\mu$s ⇒ 10^4 channel arrays, ⩾5 Hz/ch
  - needs new techniques: Magnetic Micro-Calorimeters or TES
  - ≈5 years R&D ⇒ start in 2010

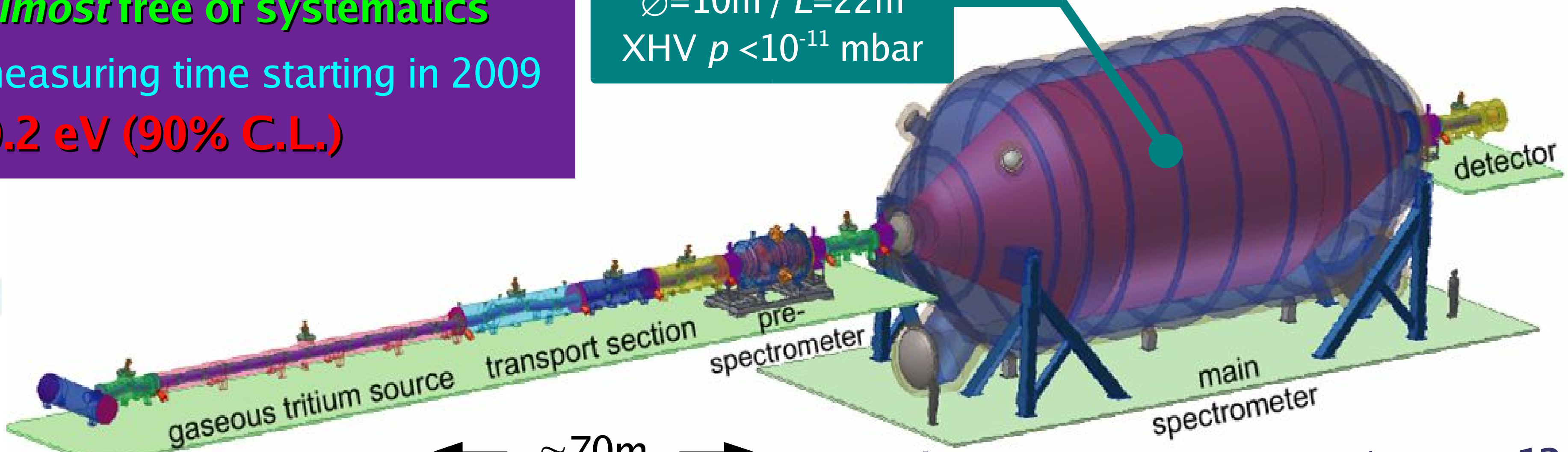
Competitiviness of a cryogenic neutrino mass experiments

- **MARE is a scalable and distributed calorimetric experiment**
  - ▷ many 10^4 channel multiplexed array *kits* to be deployed around the world
- **5+ years mesuring time starting in 2010**
  - ▸ at least $m_\nu < 0.2$ **eV (90% C.L.)**

one 10^4 channel array deployed each year for 5 years



- **KATRIN focuses on a 30 eV interval below E_0 *almost* free of systematics**
- 3 years measuring time starting in 2009
  - ▸ $m_\nu < 0.2$ **eV (90% C.L.)**

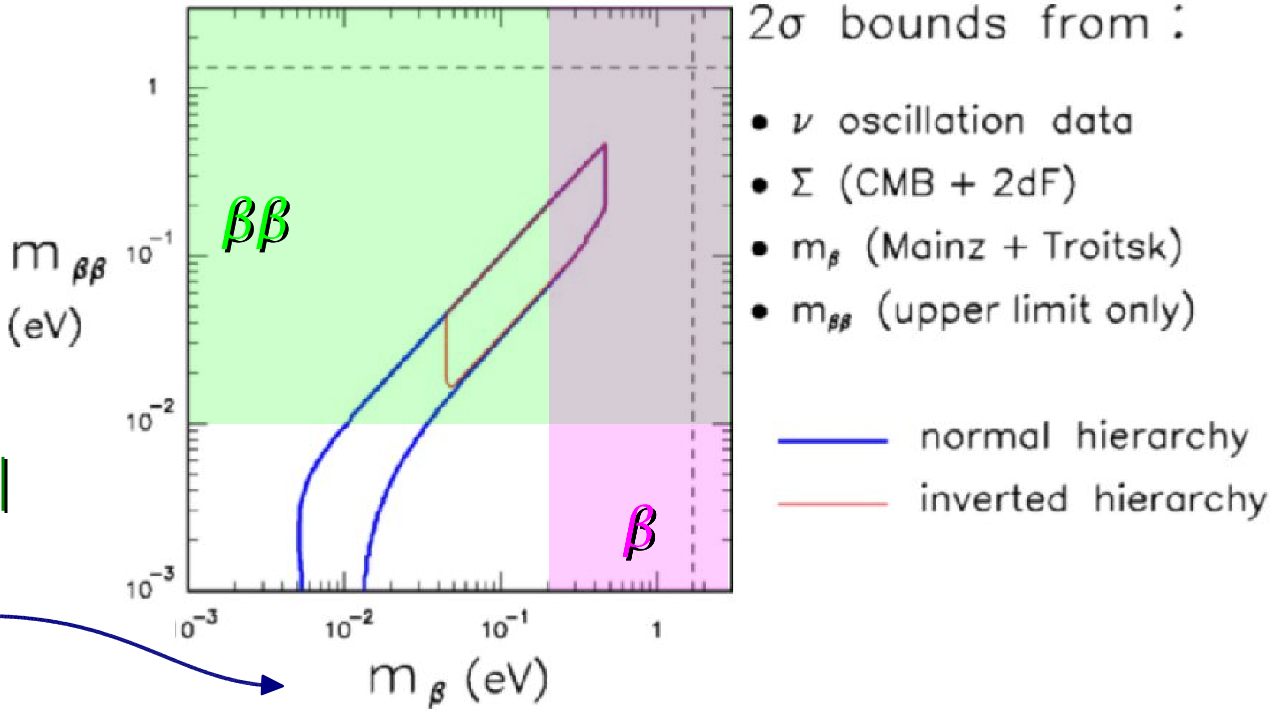


MAC-E spectrometer
∅=10m / L=22m
XHV $p < 10^{-11}$ mbar

Neutrino masses from single β and ββ-0ν decays

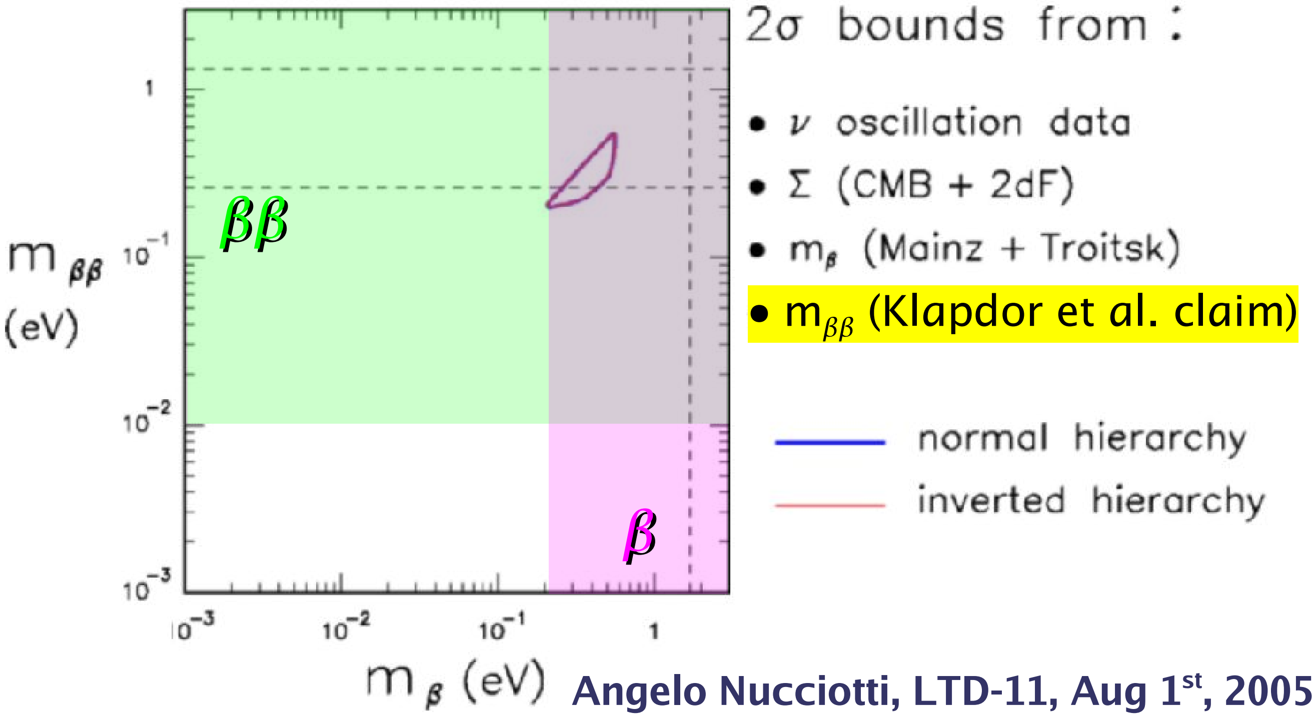
from ββ-0ν **searches**

$m_{\beta\beta} \equiv \langle m_\nu \rangle = |\sum_k m_{\nu k} \eta_k |U_{ek}|^2|$



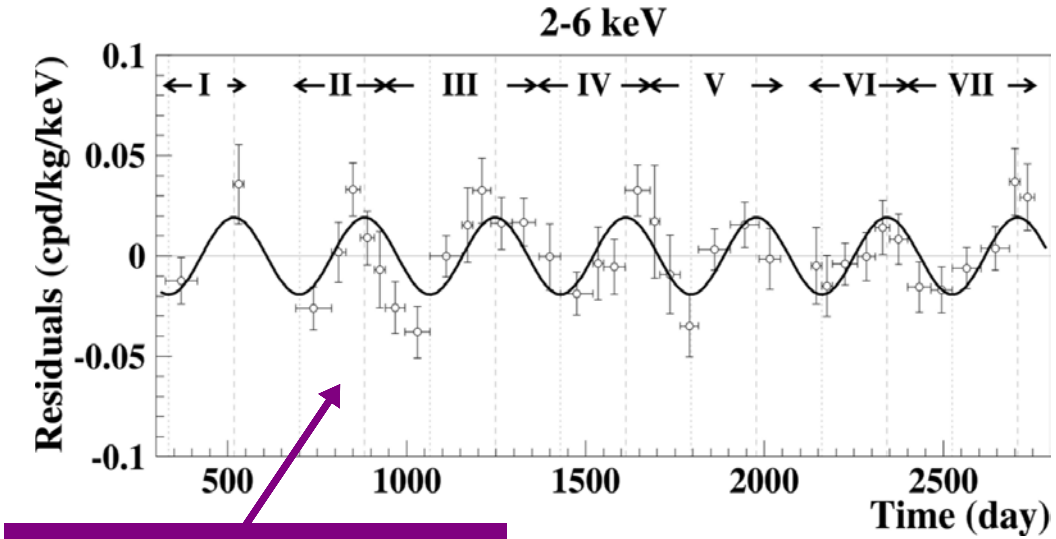
from β **decay**

$m_\beta \equiv m_\nu = (\sum_k m_{\nu k}^2 |U_{ek}|^2)^{1/2}$

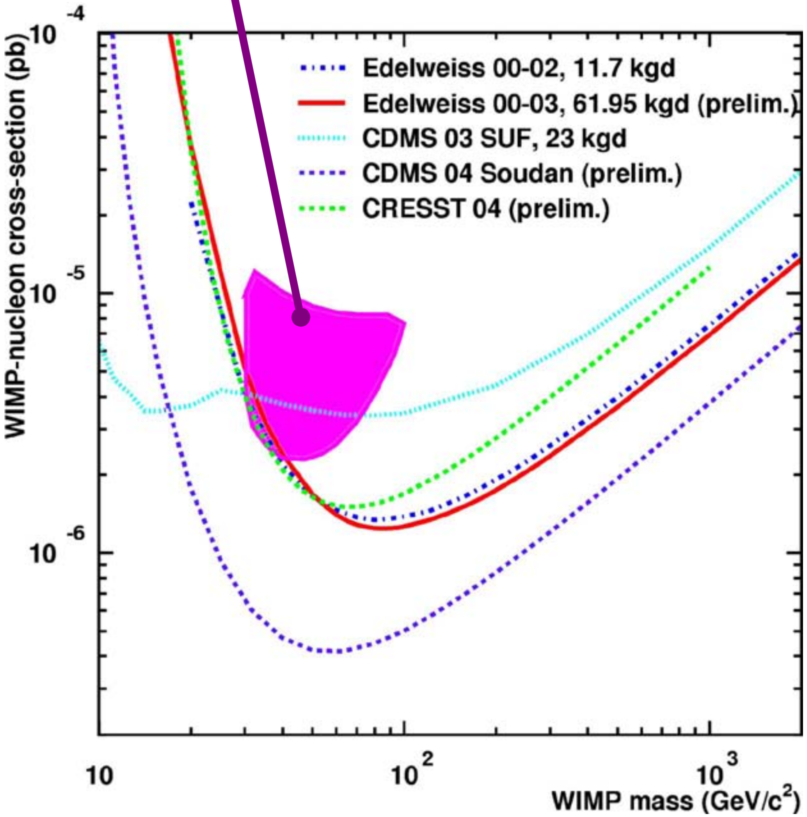


Fogli et al. hep-ph/0408045
Fogli et al. hep-ph/0506083

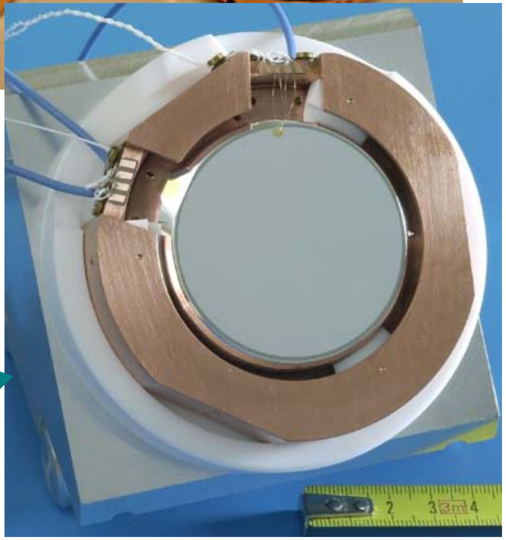
Situation of direct dark matter searches



DAMA/NaI ≈10^5 kgd



CRESST light+heat

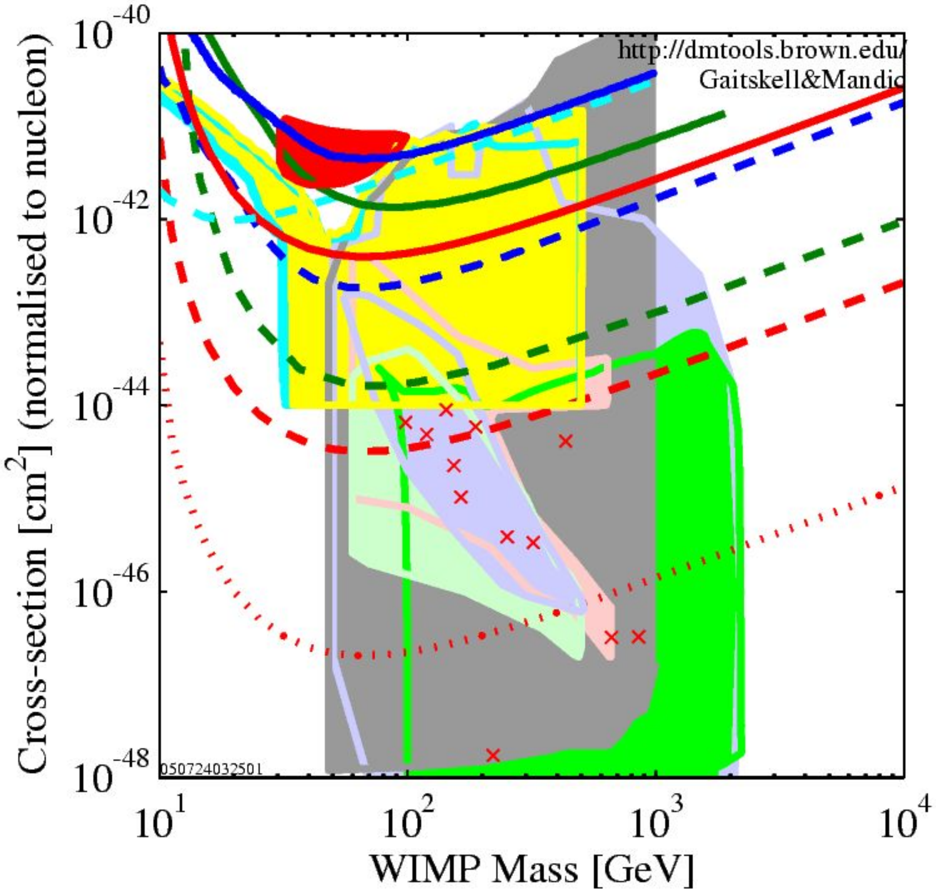


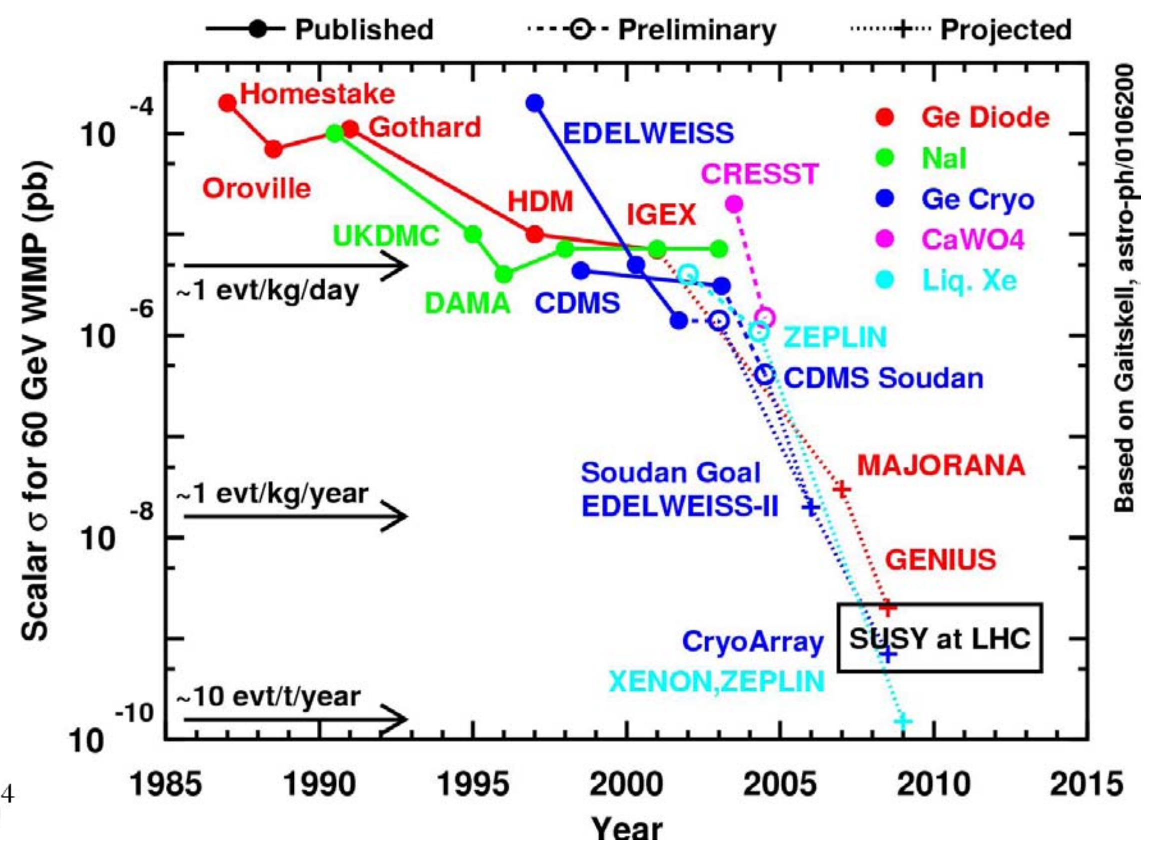
Edelweiss/CDMS ionization+heat

- the tension is releasing
  - the cryogenic direct searches are ruling out the DAMA positive result
- the power of e/γ-recoil discrimination
  - limited exposure cryogenic experiments prevail over brute-force standard ones

Future DM experiments

- **To probe SUSY *predictions* ($\sigma \approx 10^{-47}$cm^2)**
  - wait for LHC
  - go for 1 ton experiment with (improved) discrimination
    - technical challenge very similar to CUORE
    - ready around 2010?
  - other techniques with discrimination are catching up (two-phase LXe)





Conclusions

- today cryogenic detectors are *normal* for $\beta\beta$-0ν and DM searches
- next generation cryogenic detector experiments need *just* a scaling with moderate detector improvements
  - we are designing now the experiments will start data taking in 2010-15
- cryogenic detectors may have the opportunity to discover something!
- more work must be devoted to make systems reliable and detectors uniform
- radioactive background remains an issue for all techniques
- other techniques are developing new innovative approaches
  - for other 5-10 years cryogenic detectors will lead these fields thanks to the past years R&D