Review of underground physics

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27 May - 4 June 2019 - Otranto (LE) , Italy

Lecture n. 2

IDPASC

Otranto School

Outline

- Motivations
- Rare event physics
- Underground laboratories

Astro-particle:
- Neutrino physics
- Rare Nuclear decays
- Dark matter
- …

Other:
- Nuclear reactions
- Gravitational waves
- Fundamental physics
- Technology
- Biology
- …

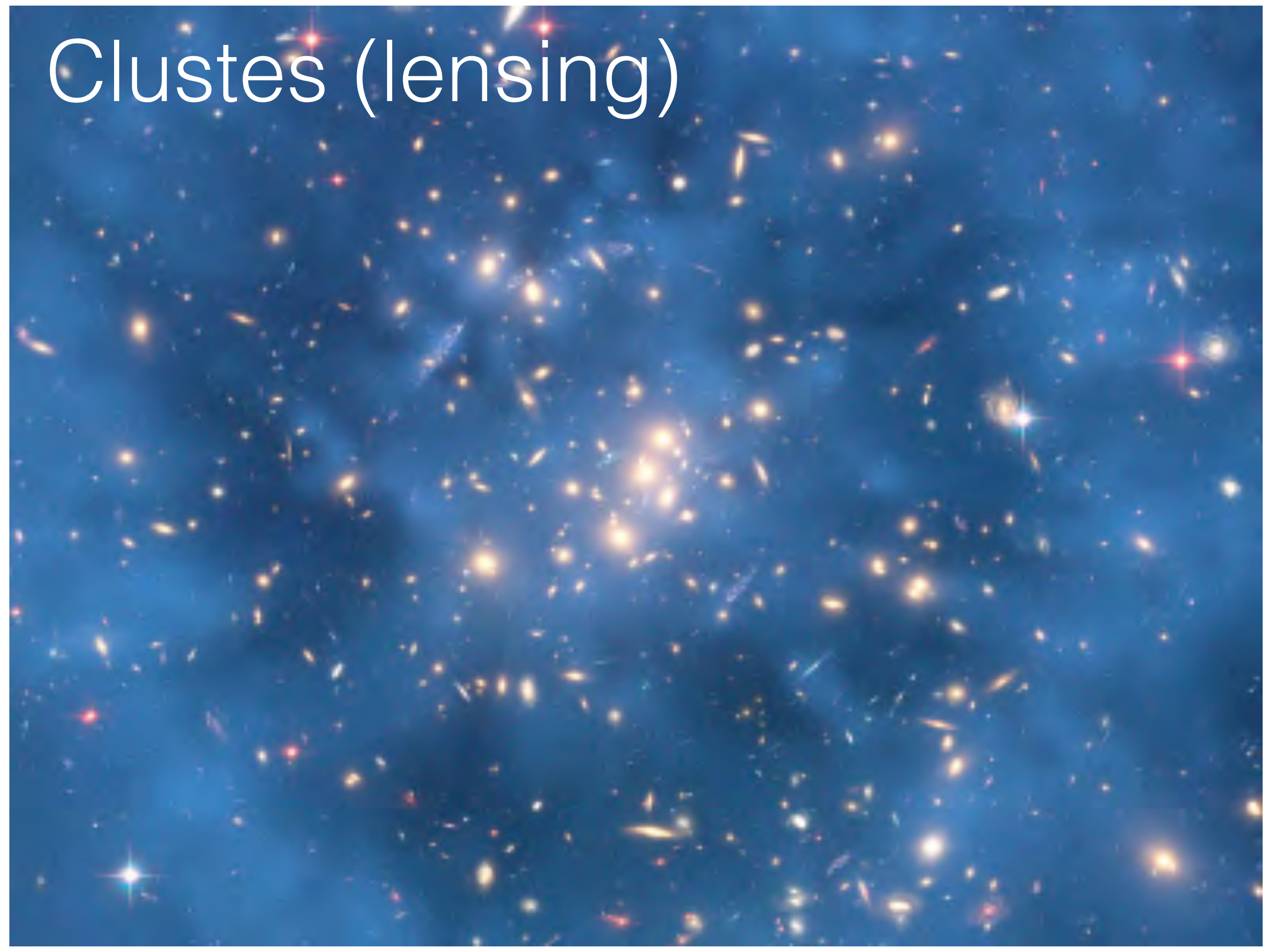
No mention to:
- Under-water
- Under-ice

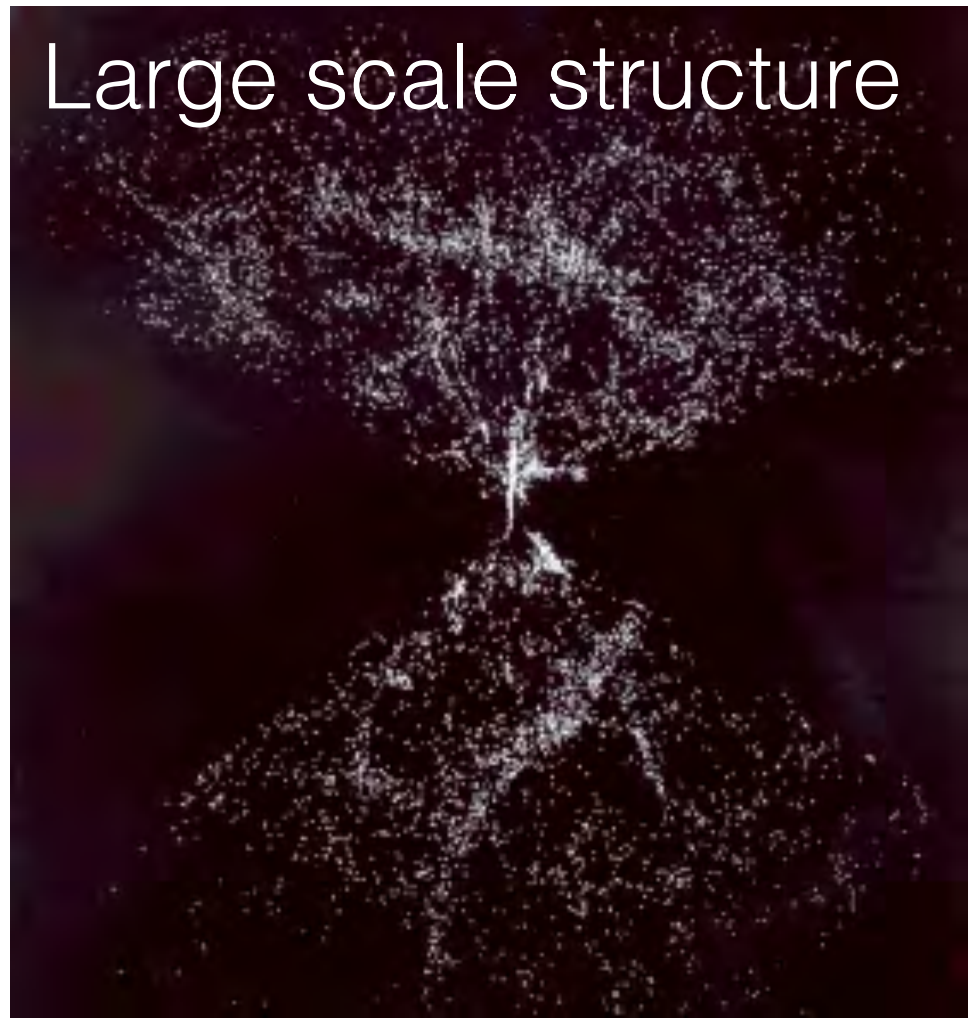
Dark Matter Searches

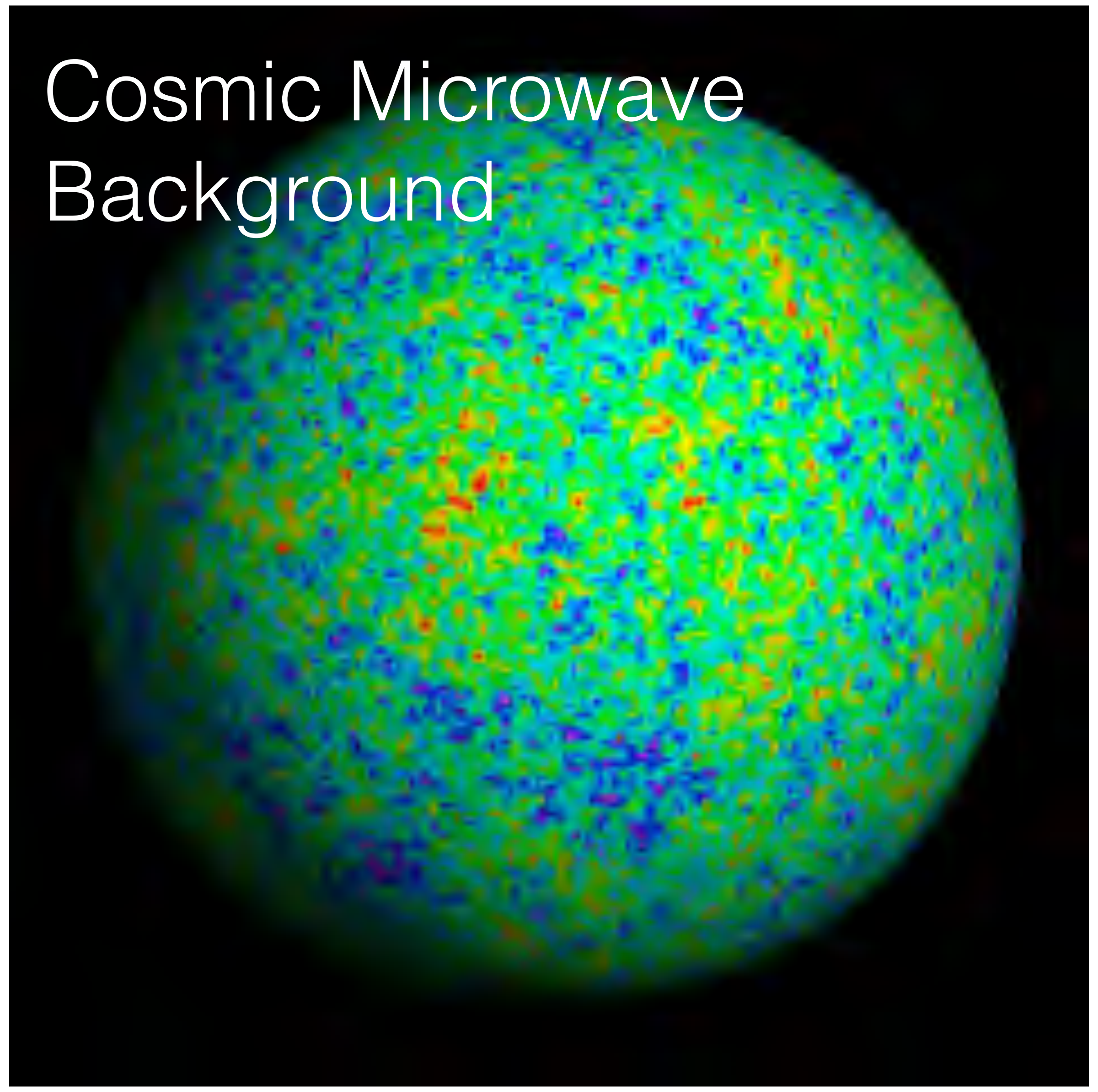
Brief history

- 1922: J.C. Kapteyn coined the name ‘dark matter’, in studies of the stellar motion in our galaxy (he found that no dark matter is needed in the solar neighbourhood)
- 1932: J. Oort suggested that there would be more dark than visible matter in the vicinity of the Sun (later the result turned out to be wrong)
- 1933: F. Zwicky found ‘dunkle Materie’ in the Coma cluster (the redshift of galaxies was much larger than the escape velocity due to luminous matter alone)
- 1970s: V.C. Rubin & W. Ford: flat optical rotation curves of spiral galaxies, 1978: Bosma, radio

Astronomical evidence







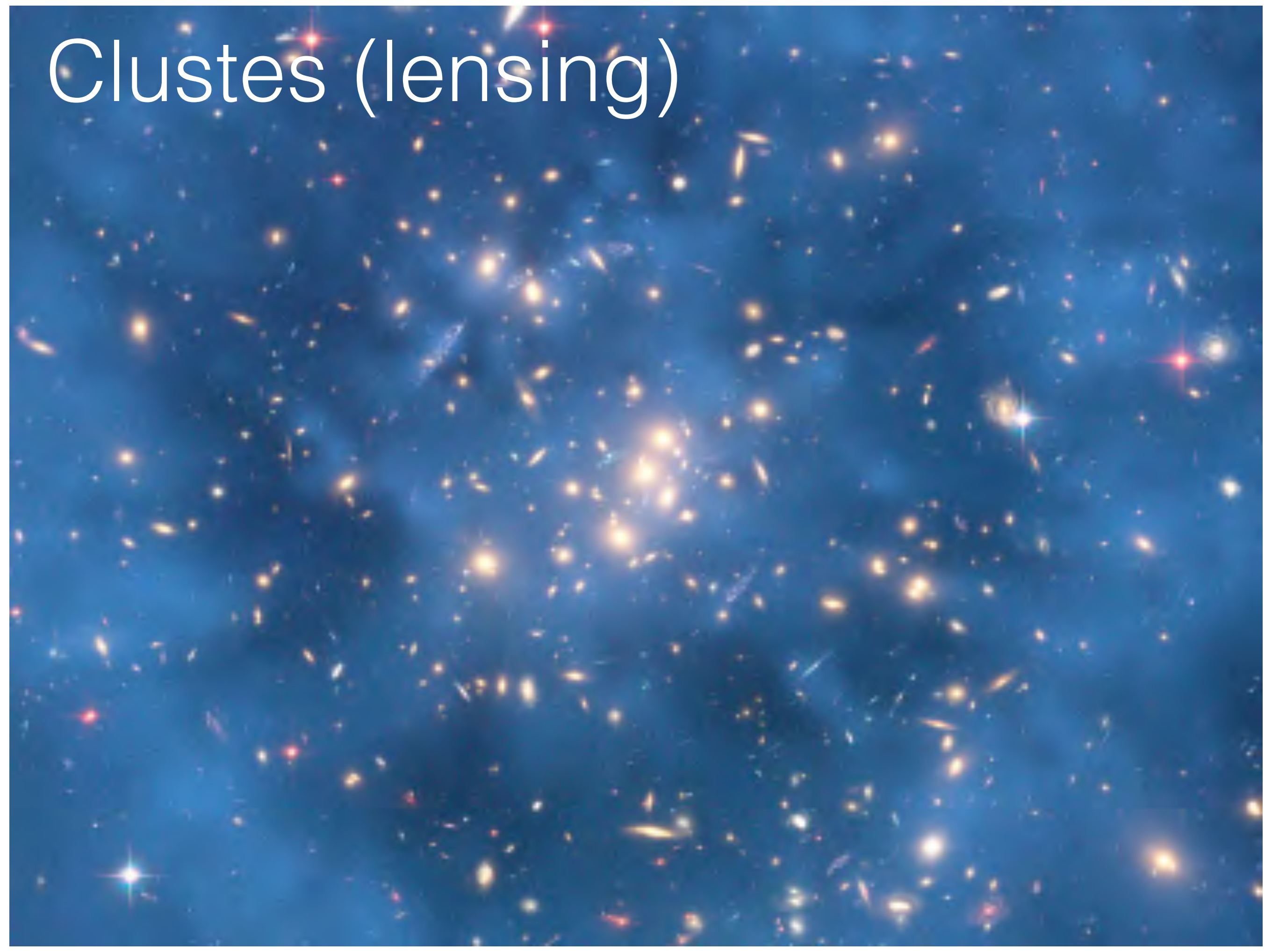
A consistent picture:

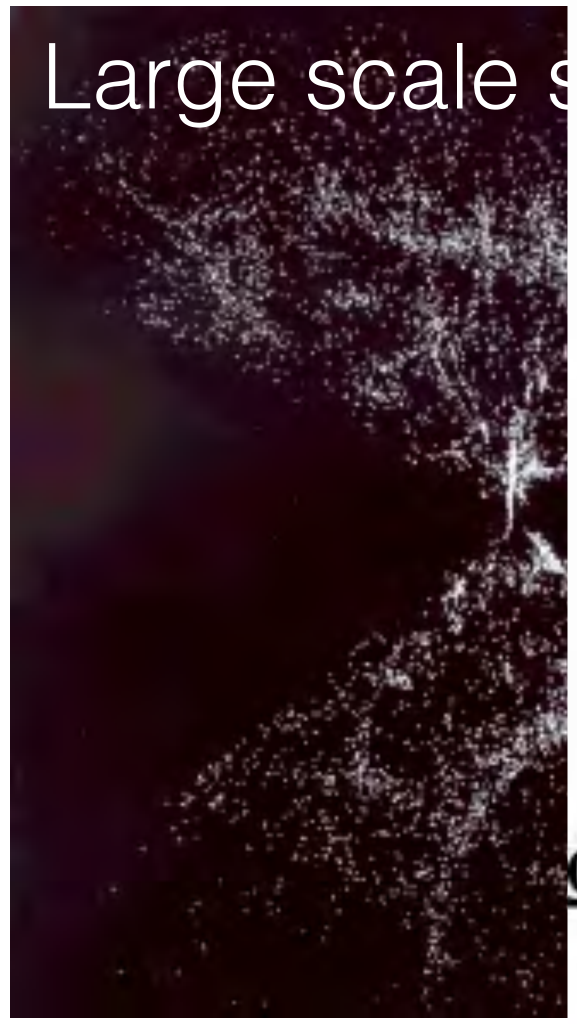
~32% matter

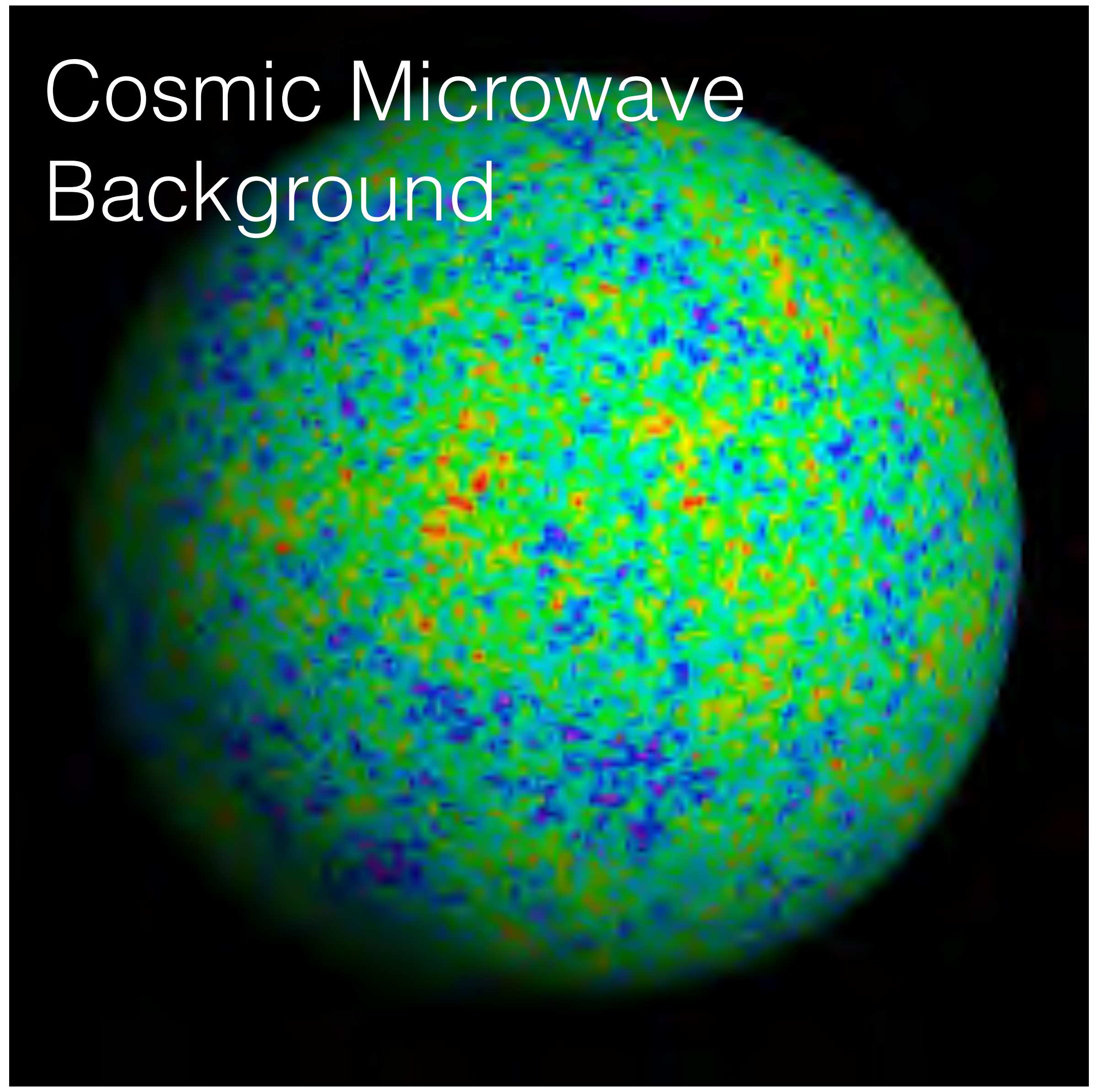
~68% dark energy

- Ordinary Matter
- Dark Matter
- Dark Energy

Astronomical evidence





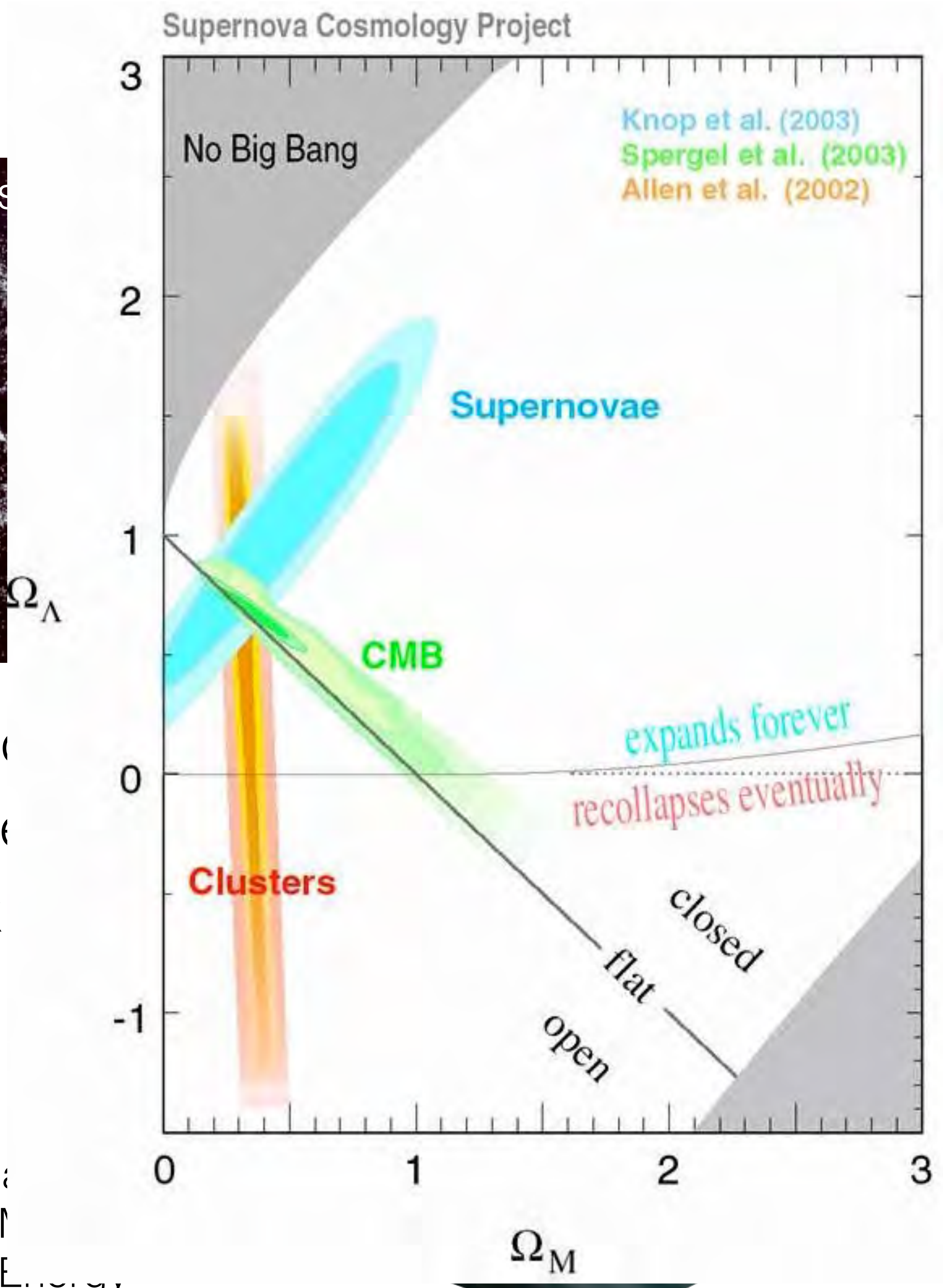


A consistent pi

~32% matte

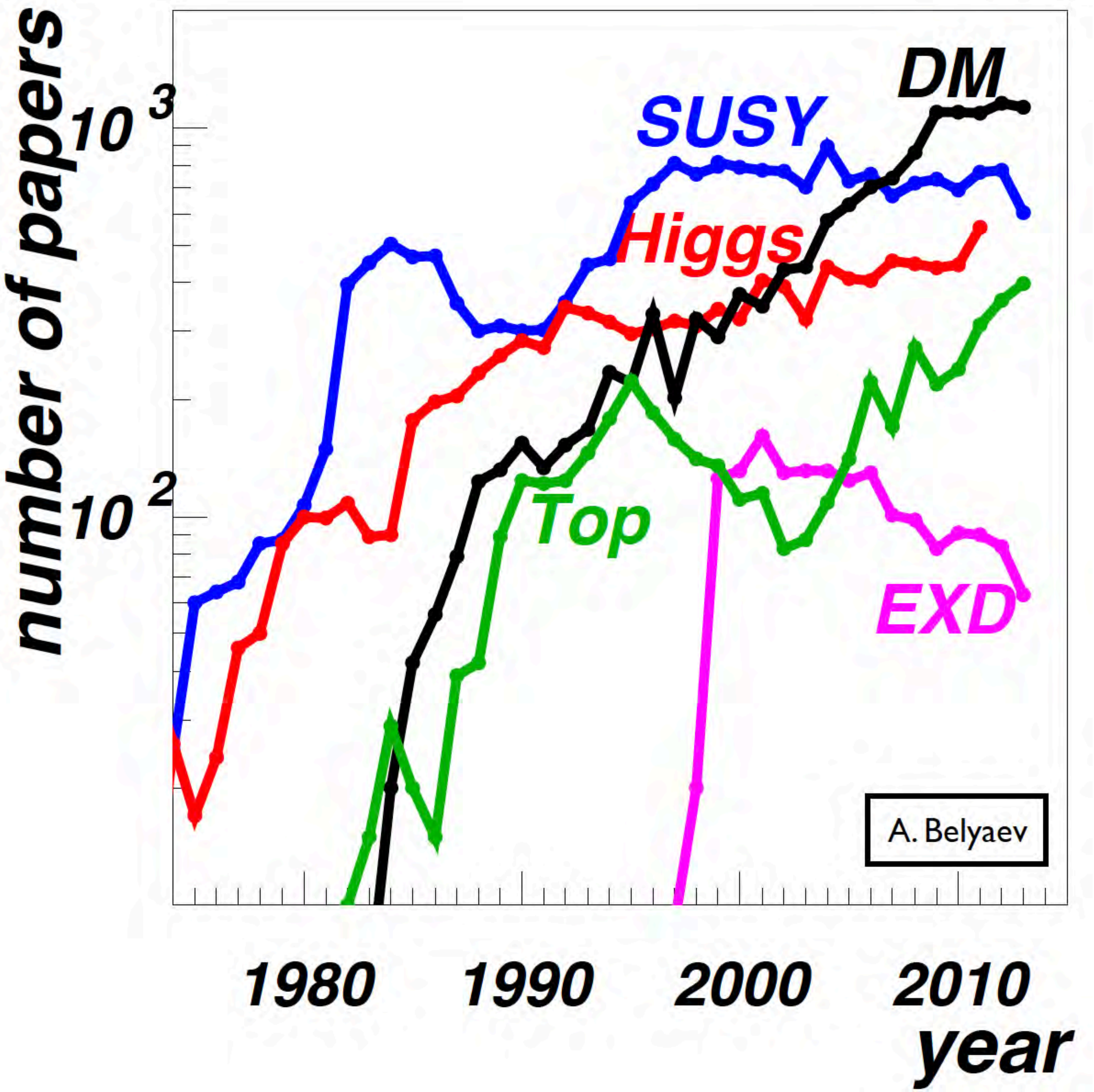
~68% dark

- Ordina
- Dark M
- Dark E



Open questions

- The dark matter puzzle remains fundamental: dark matter leads to the formation of structure and galaxies in our universe
- We have a standard model of CDM, from 'precision cosmology' (CMB, LSS): however, measurement ≠ understanding
- For ~85% of matter in the universe is of unknown nature



Particle dark matter?

- What do we know about dark matter?
  - Dark (neutral: no electric or color charge)
  - Massive (to explain gravitational effects)
  - Stable or with a lifetime of the order of the age of the Universe itself (still around today).

- ☐ Mass: ______
- ☐ Spin : ______
- ☐ Exactly Stable? ☐ Yes ☐ No
- ☐ Couplings:
  - ☑ Gravity
  - ☐ Weak Interaction?
  - ☐ Higgs?
  - ☐ Quarks / Gluons?
  - ☐ Leptons?
  - ☐ Self-Interacting?
  - ☐ Cosmological production

- In the **Standard Model (SM)** of particle physics only neutrinos could work (hot dark matter)
- However, models **beyond SM** predict a number of NEW particles. Many of them satisfy the requests:
  - Neutralino in Supersymmetry, gravitino, Axion, LKP in extra dimensions, Sterile neutrino, Super-heavy dark matter and many others
- In one word: **WIMP's** (Weakly Interacting Massive Particles)

WIMP's

- Well motivated theoretical approach (BSM models)

- In the primordial Universe particles are in thermal equilibrium:

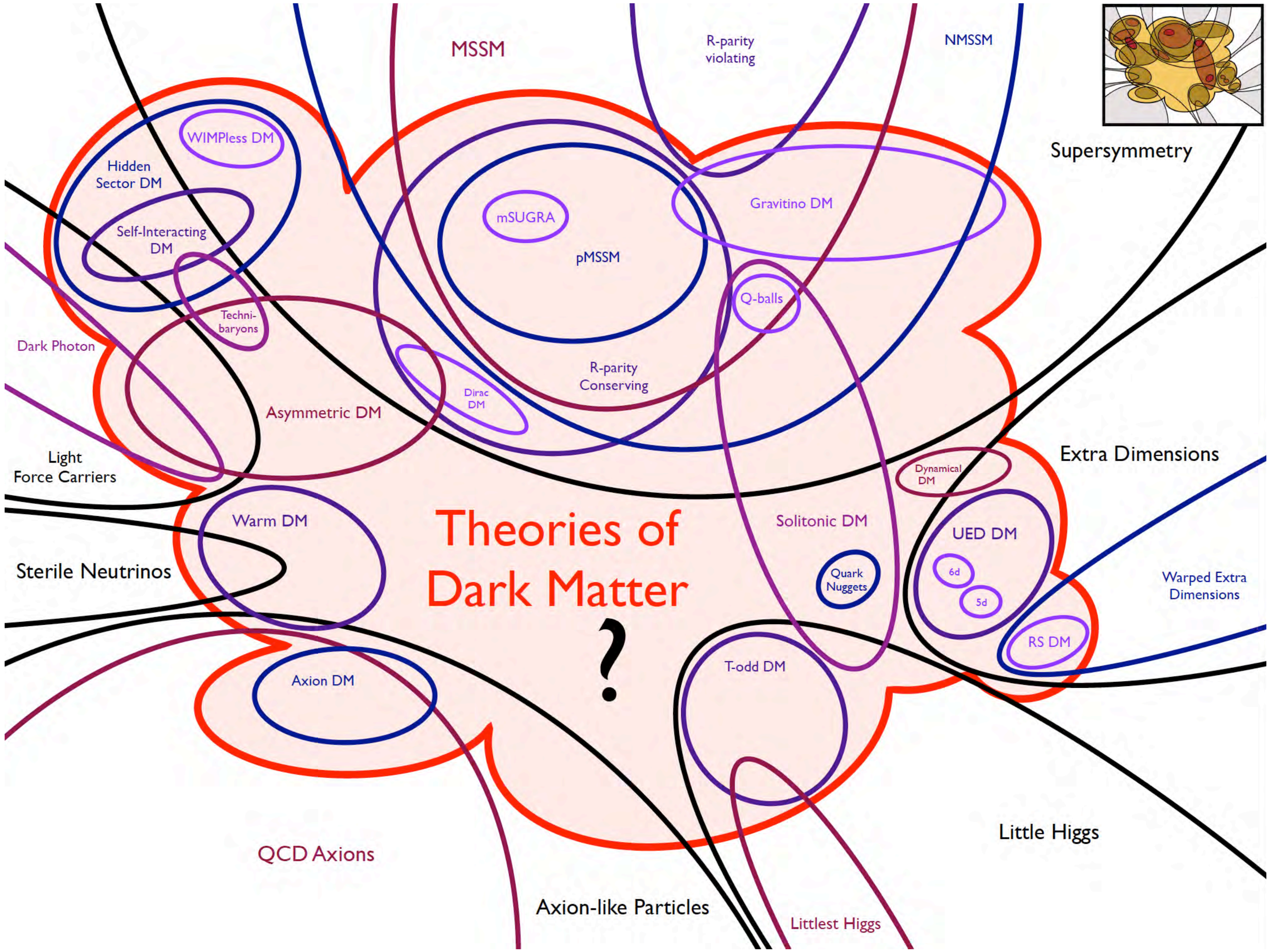
creation vs. annihilation

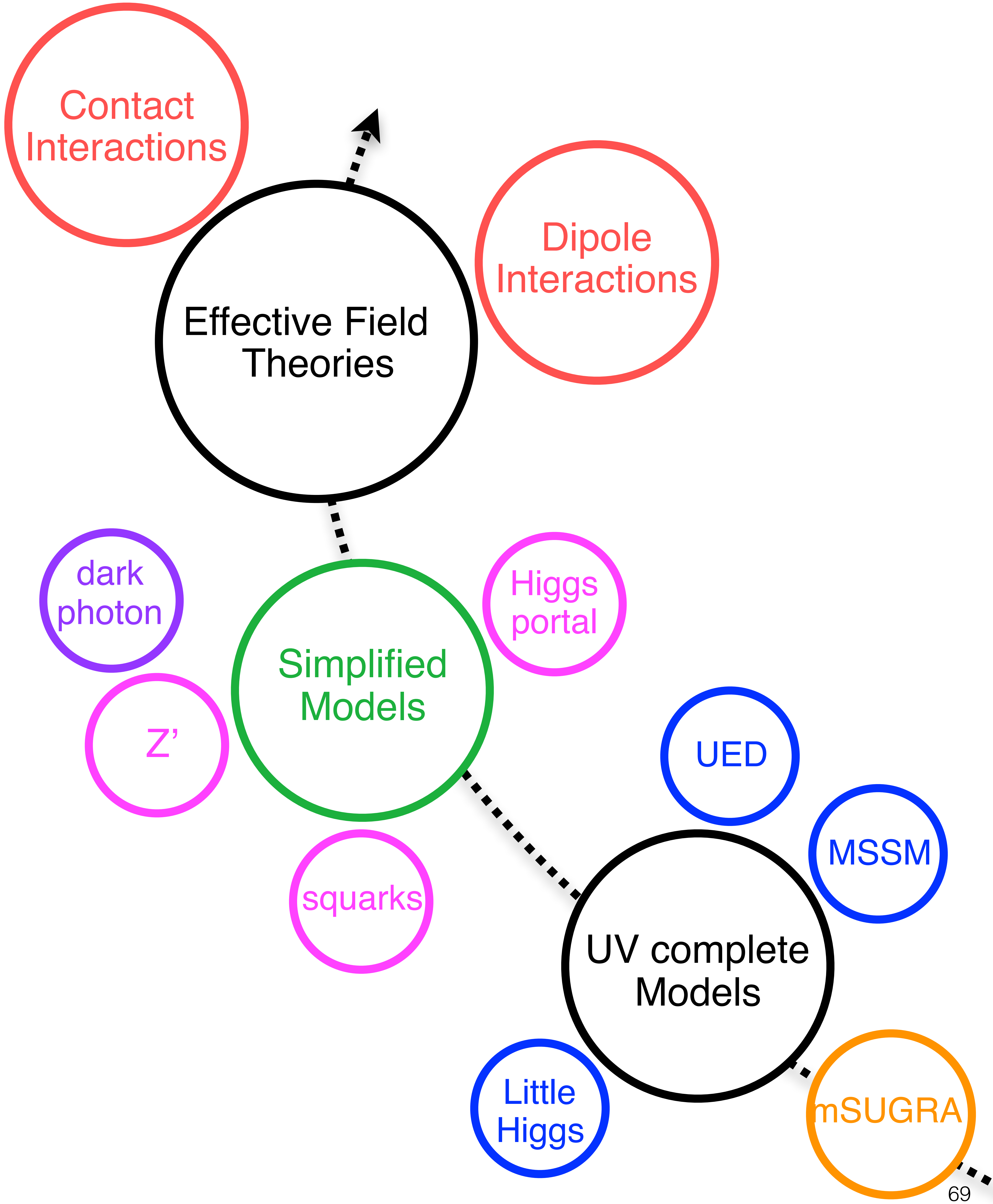
$\chi\bar{\chi} \leftrightarrow \ell^+\ell^-, q\bar{q}, W^-W^+, Z\bar{Z}$

- The annihilation rate decreases with the Universe expansion
- Each process breaks the equilibrium at different ages and freeze out

- WIMP models predict correct relic densities for an annihilation rate on the weak scale

A complex theoretical scenario



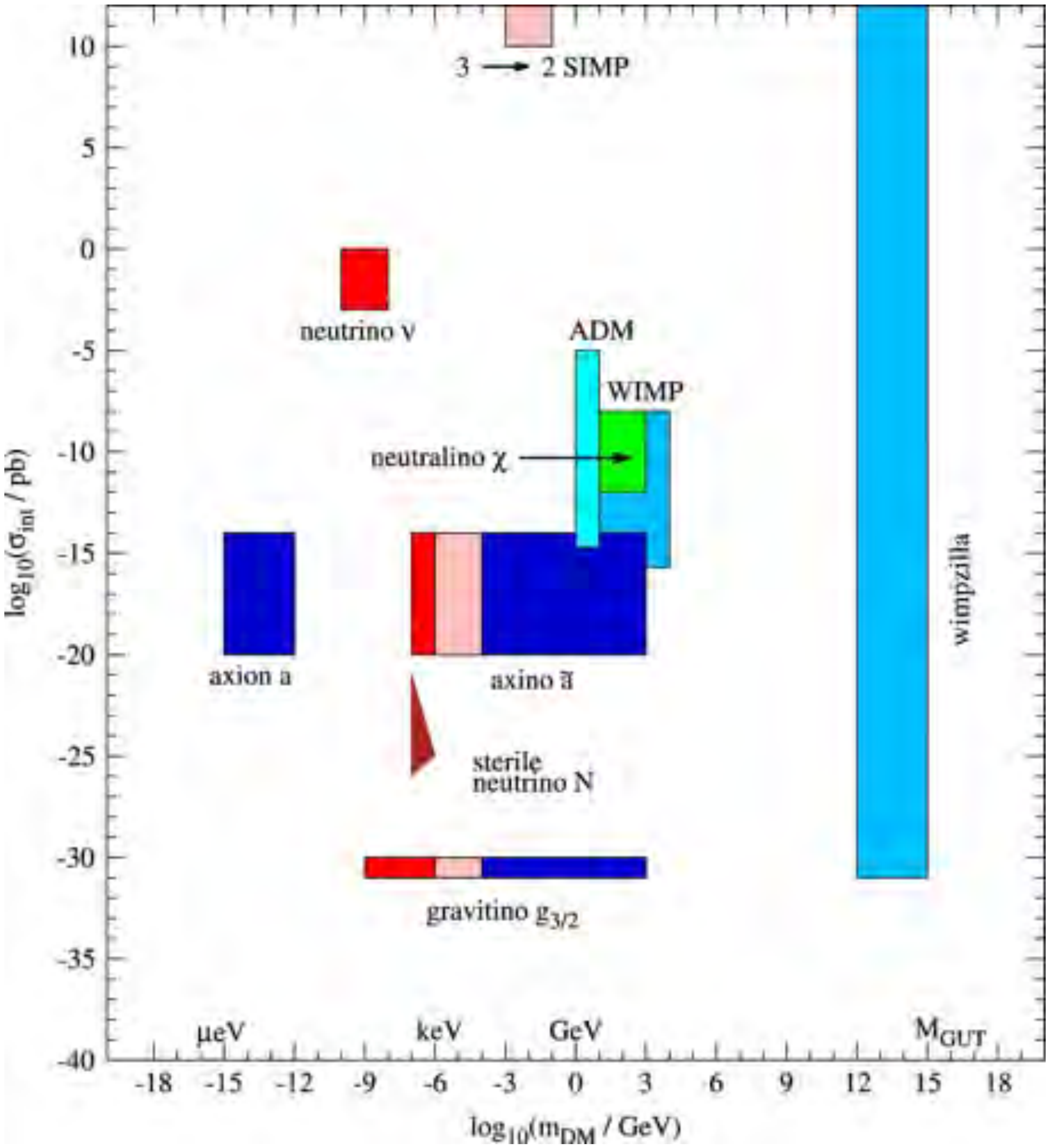


Parameter space

- Masses & interaction cross sections span an enormous range

- Most dark matter experiments optimised to search for WIMPs
- However also searches for axions, ALPs,
- SuperWIMPs, etc

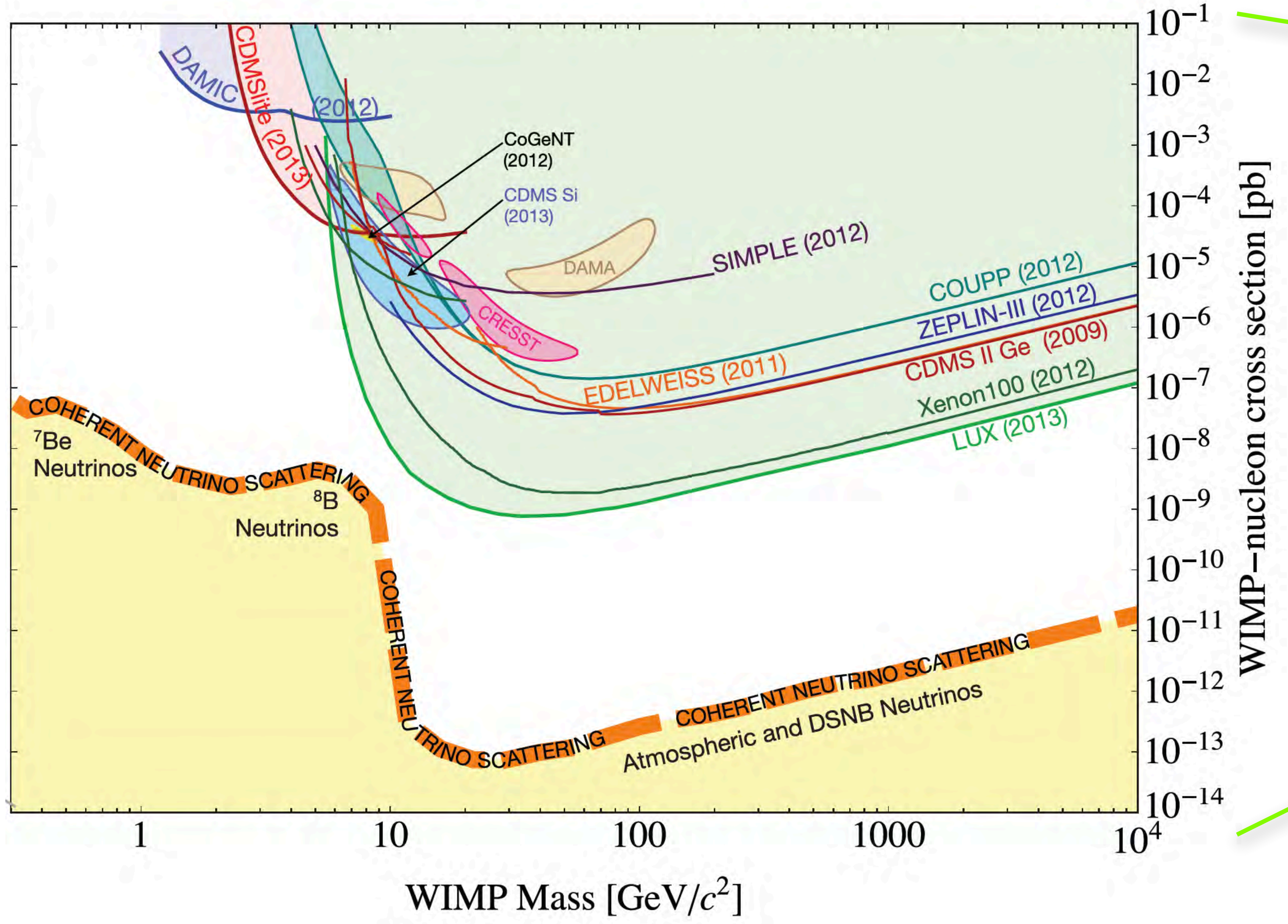
H.Baer et al, Phys. Rep. 555 (2014) 1

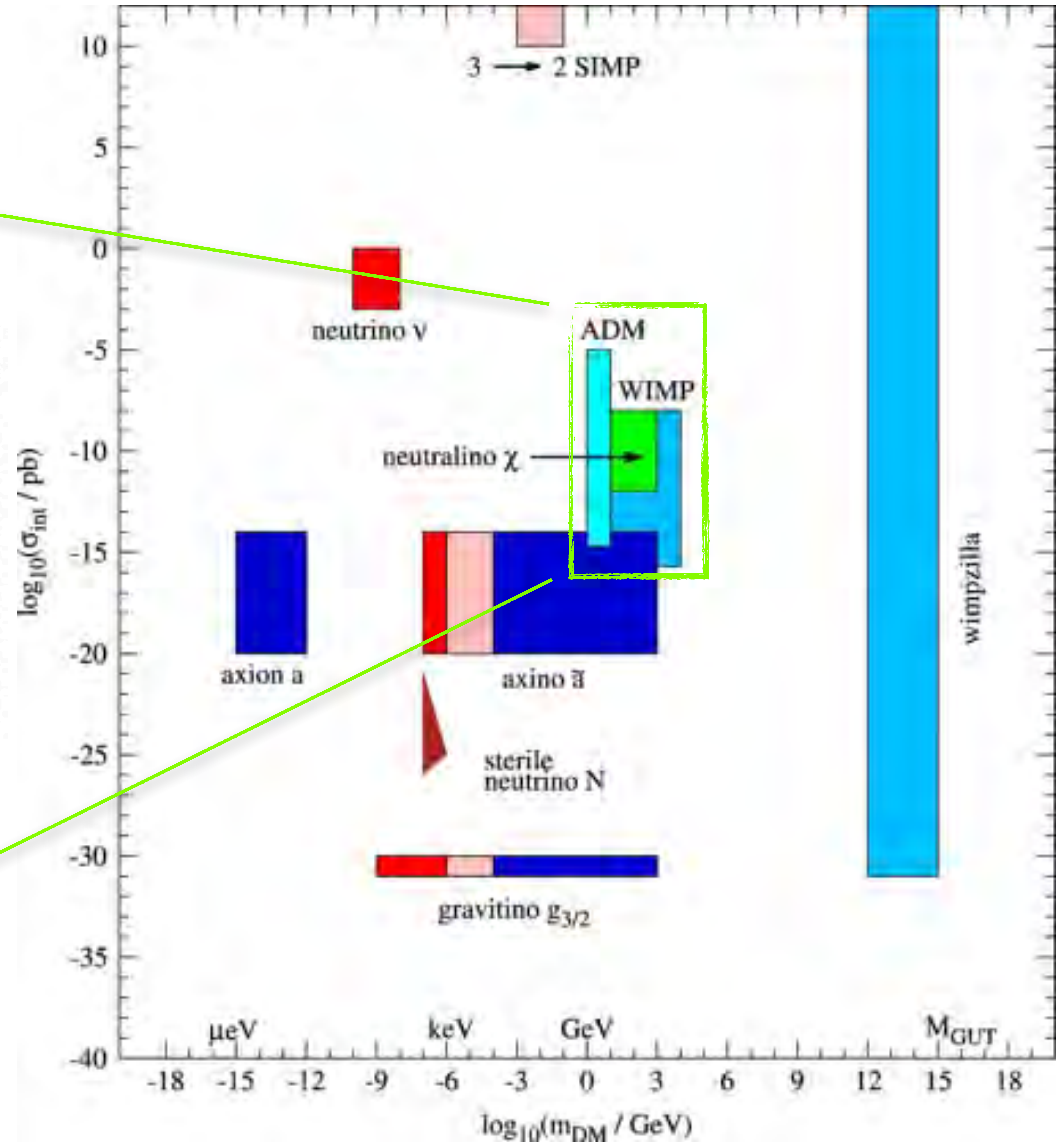


Parameter space

H.Baer et al, Phys. Rep. 555 (2014) 1

WIMPS

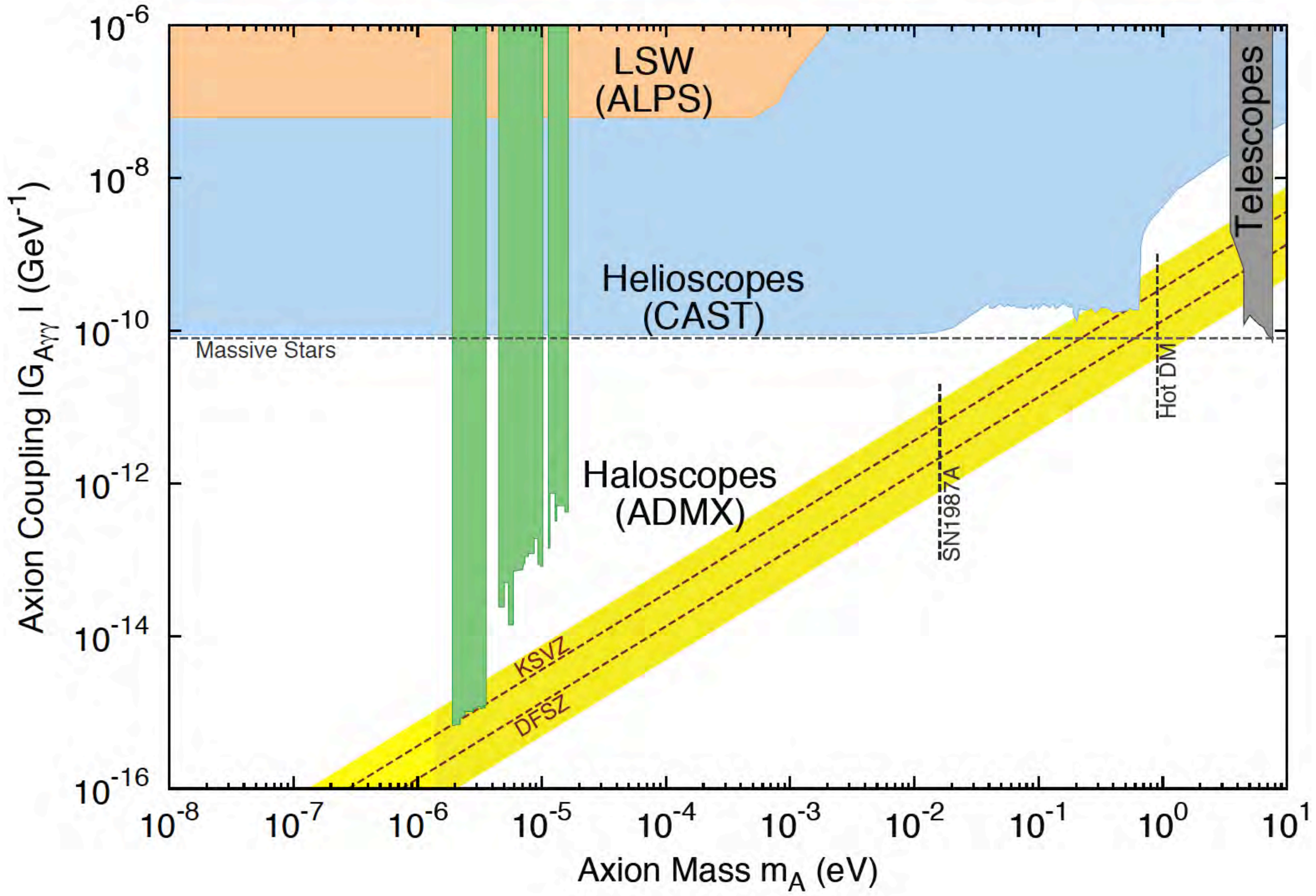


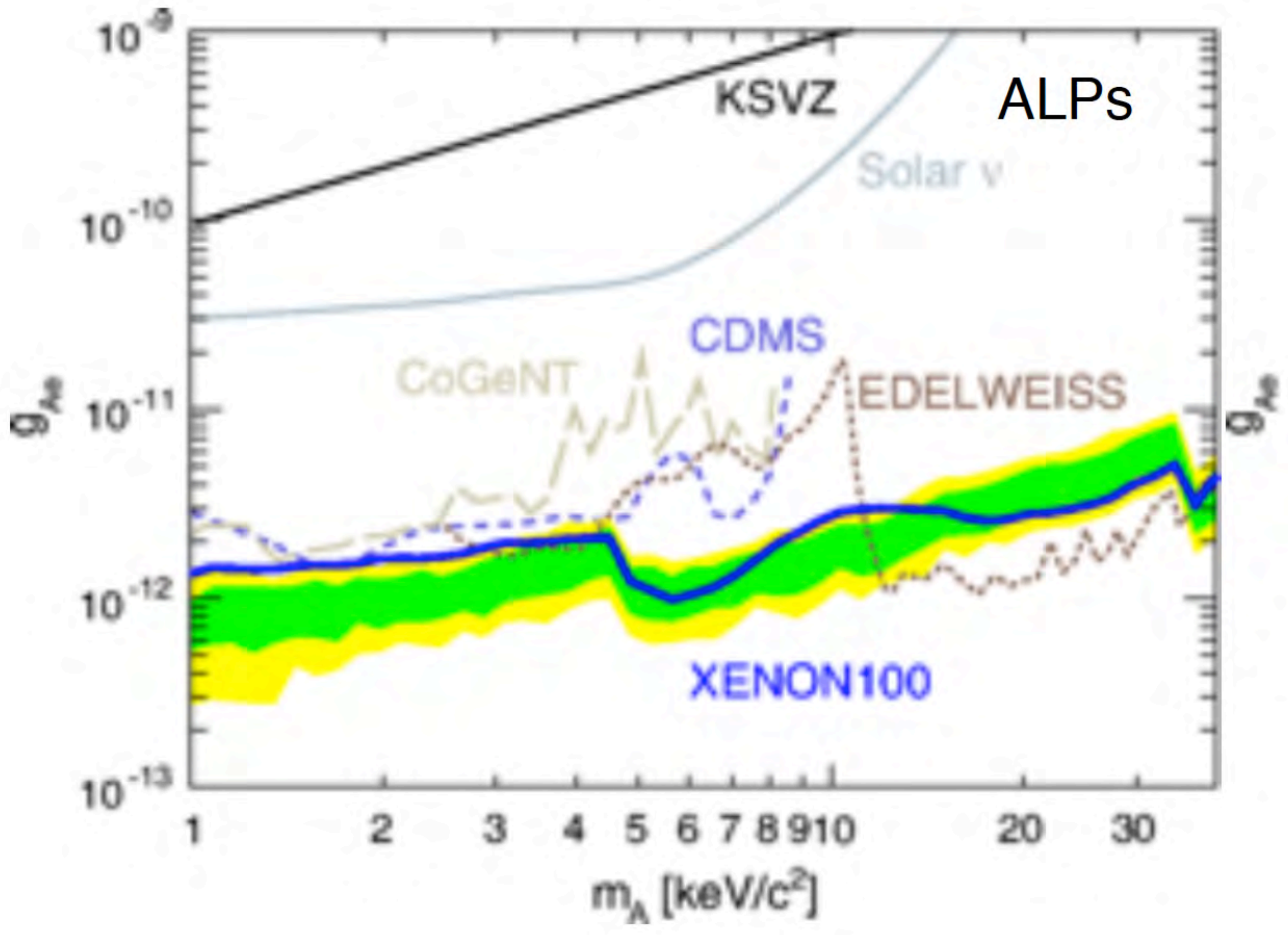


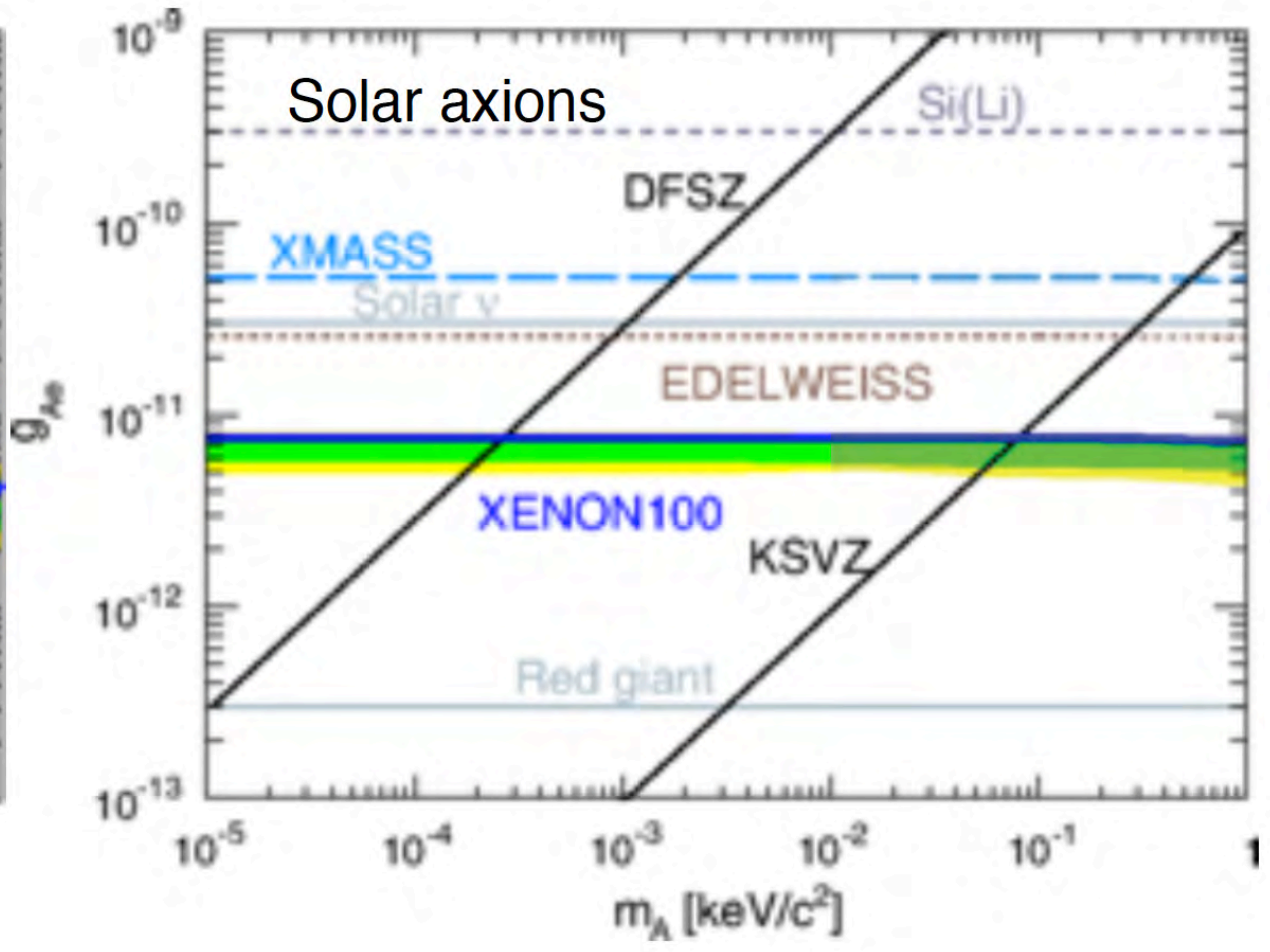
Parameter space

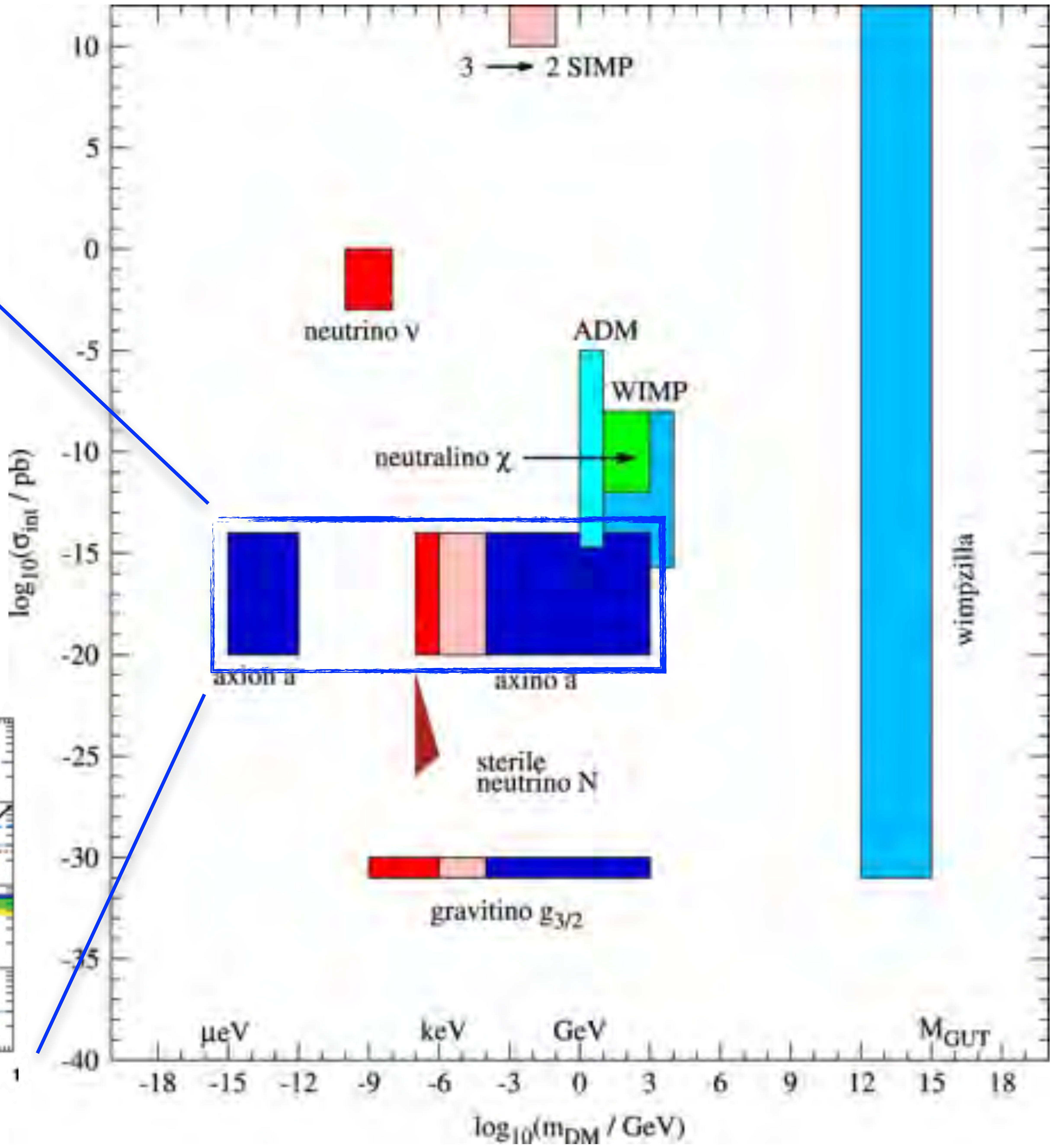
H.Baer et al, Phys. Rep. 555 (2014) 1

Axions

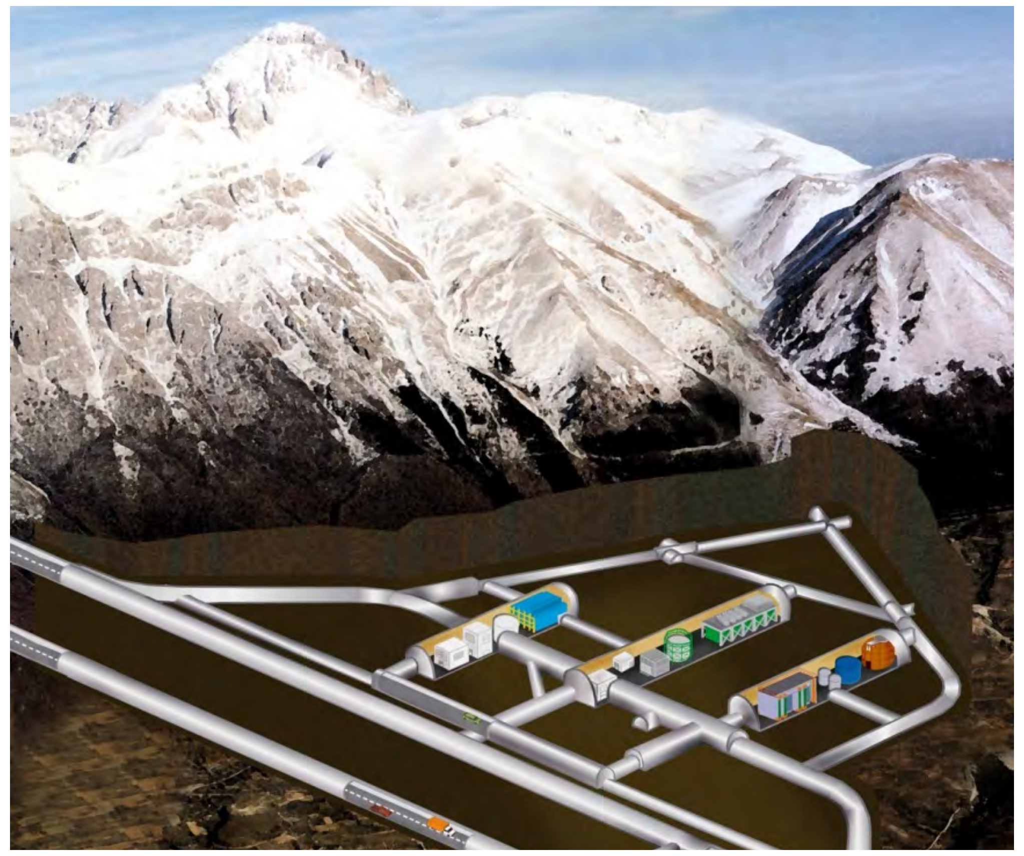


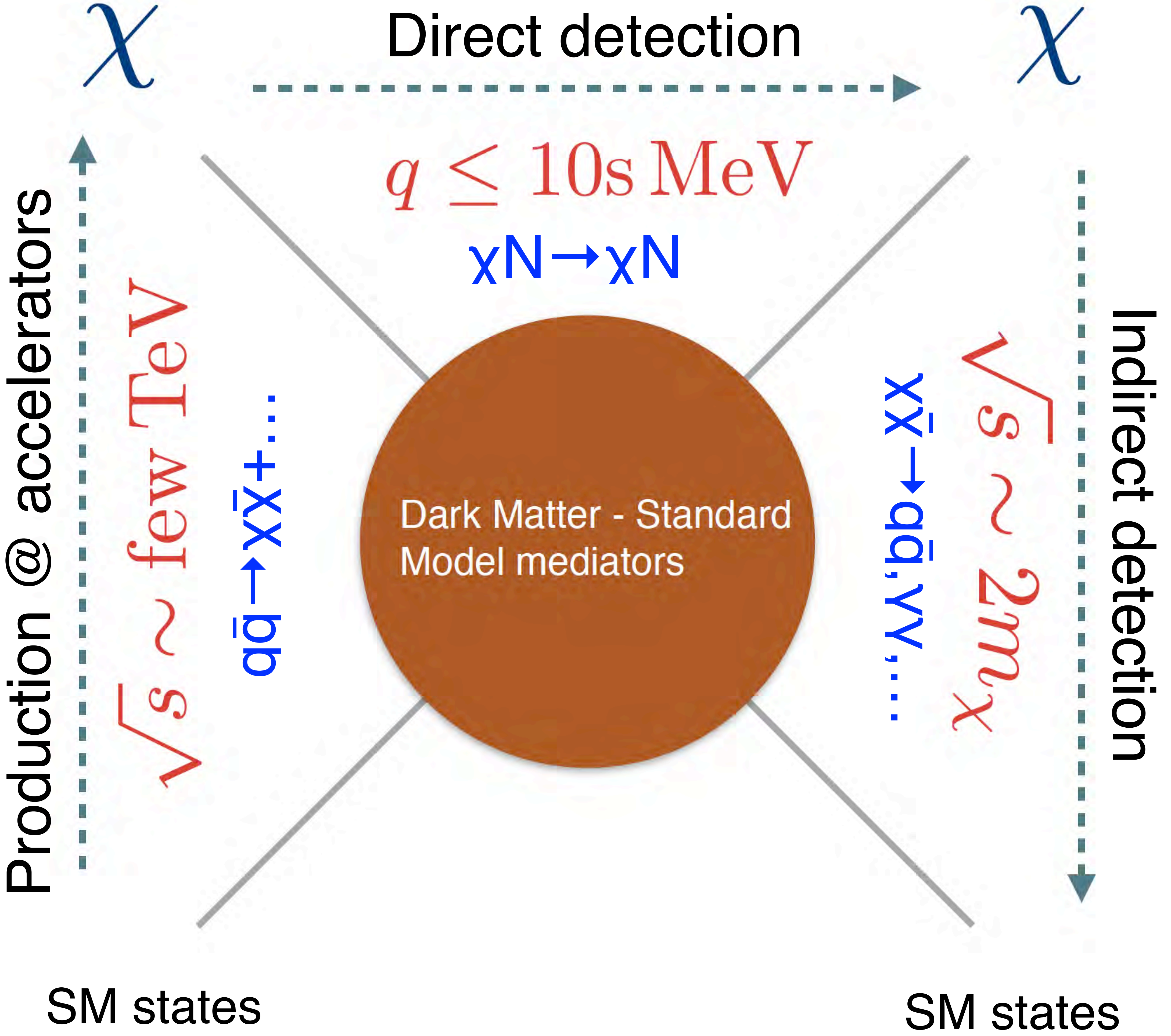






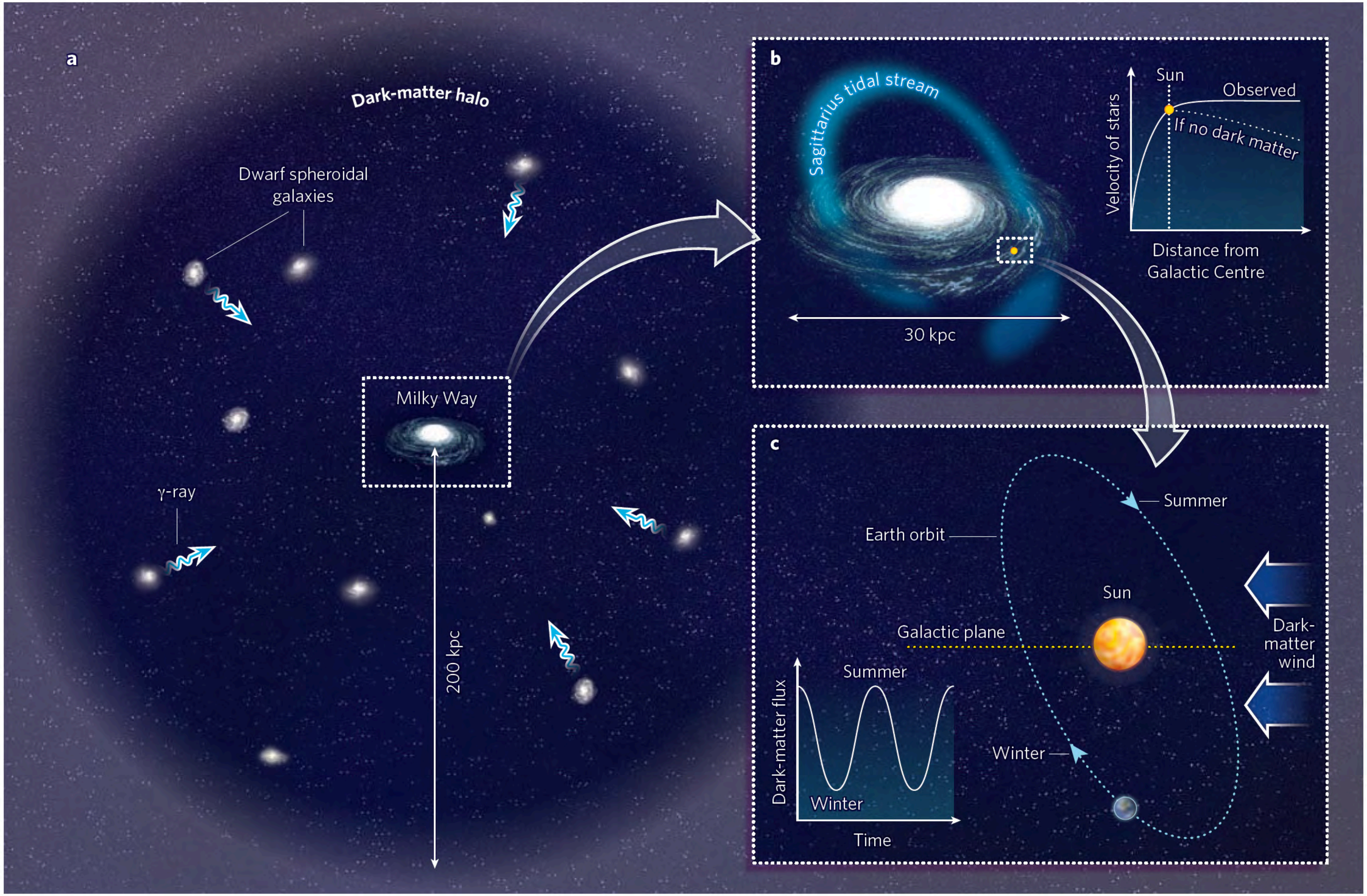
WIMP detection strategy





Astrophysics: the dark matter halo

- Our galaxy is embedded in a dark matter halo which extends well beyond (200 kpc) the milky way extension



Astrophysics

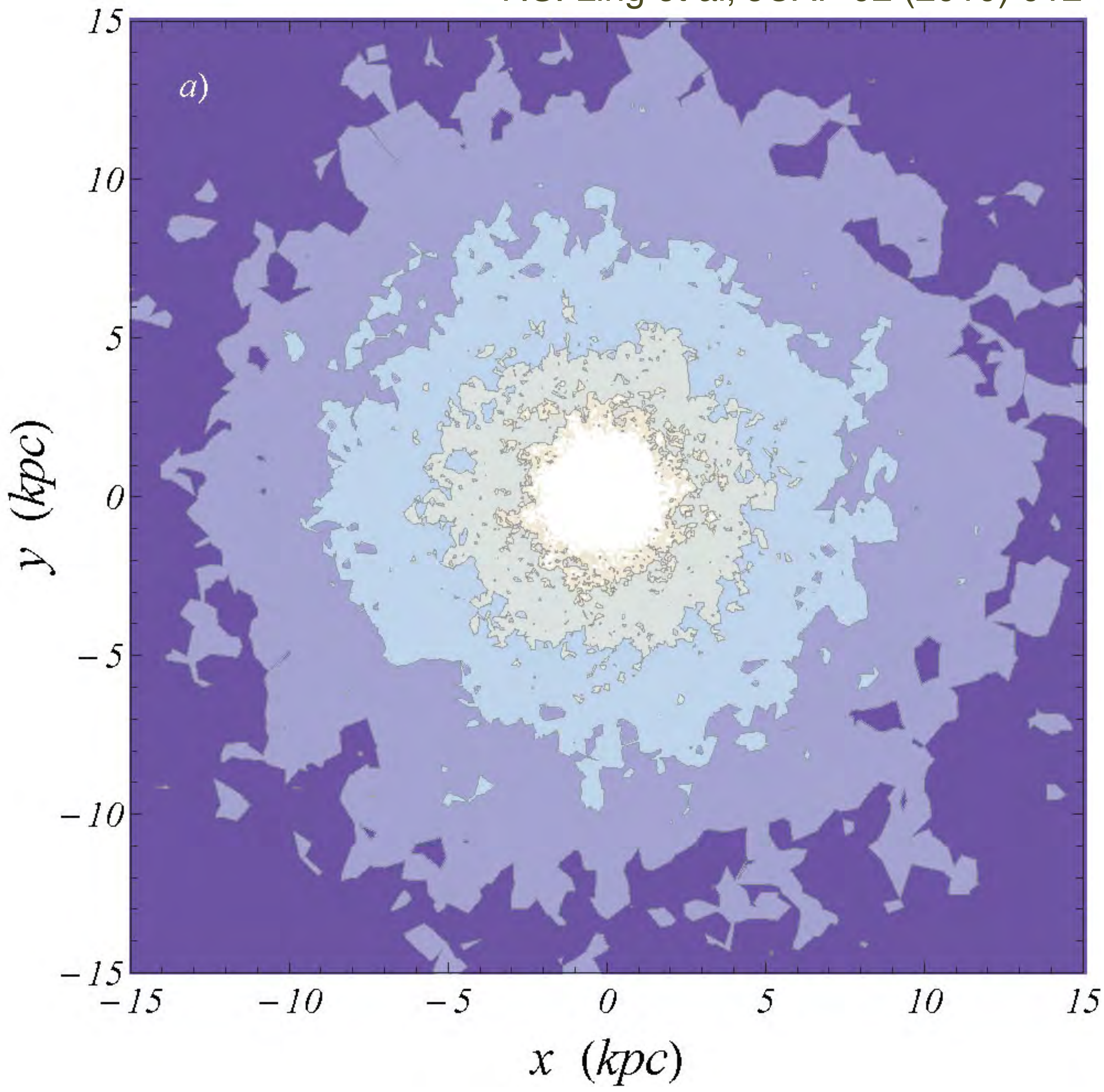
F.S. Ling et al, JCAP 02 (2010) 012

Local density (at R_0 ~ 8 kpc)

- local measures use the vertical kinematics of stars near the Sun as 'tracers' (smaller error bars, but stronger assumptions about the halo shape)
- global measures extrapolate the density from the rotation curve (larger errors, but fewer assumptions)

$$\rho(R_0) = 0.2 - 0.56\,\mathrm{GeV\,cm^{-3}} = $$
$$= 0.005 - 0.015\,\mathrm{M_\odot\,pc^{-3}}$$

➡ WIMP flux on Earth: ~10^5 $cm^{-2}s^{-1}$
(m_W=100 GeV, ρ=0.3 GeV/cm^3)



High-resolution cosmological simulation: density map of the dark matter halo ρ = [0.1, 0.3, 1.0, 3.0] GeV cm-3

The standard halo model

- Isotropic, isothermal sphere with a Maxwellian velocity distribution

$$f(v) = N \cdot exp(\frac{-3|v|^2}{2\sigma^2})$$

usually truncated: $f(v) = 0$ for $|v_i| > v_{esc}$

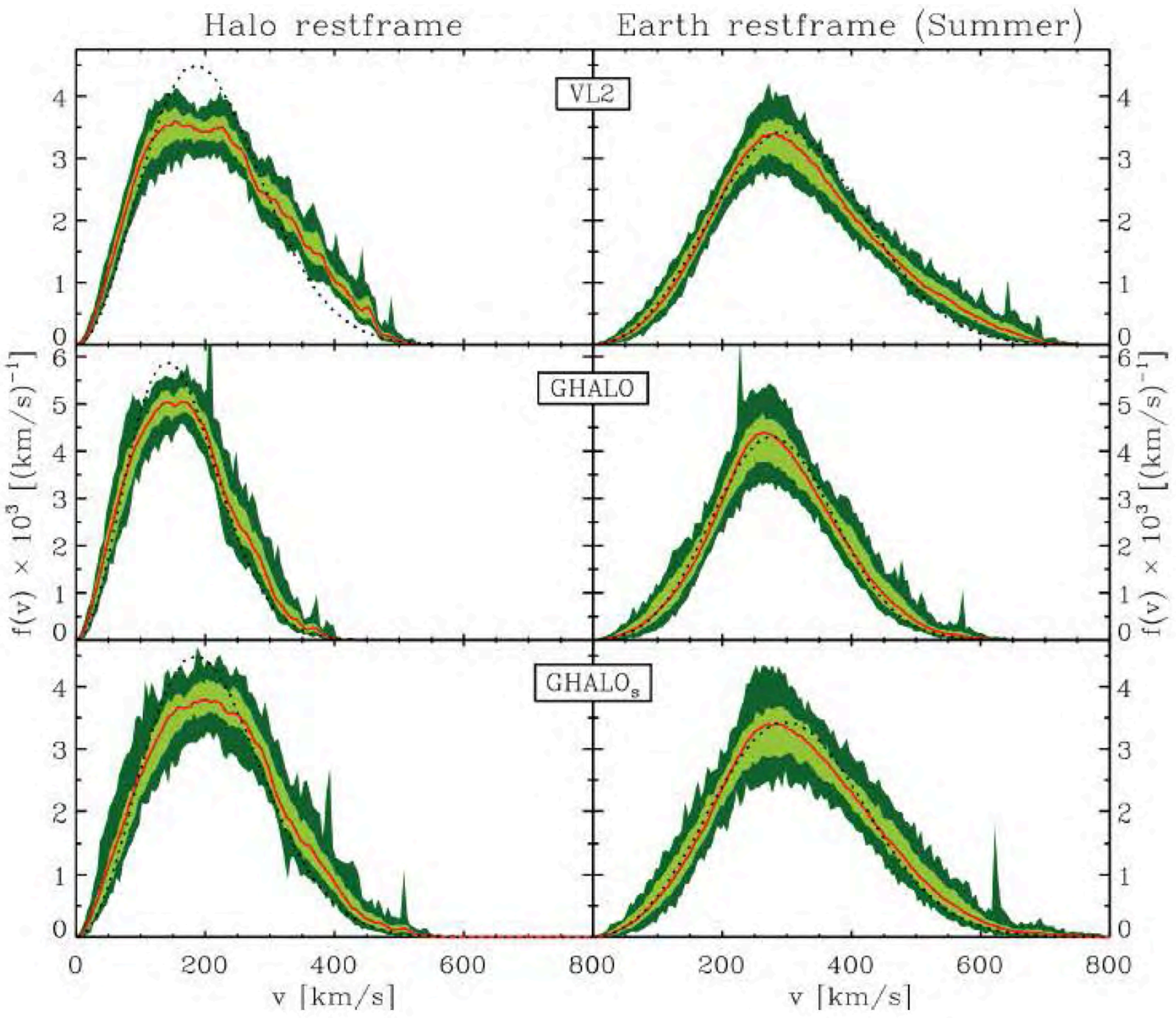
- Local density $\rho_0 = 0.3$ GeV/cm^3 = 0.008 $M_\odot$ /pc^3 = $5 \cdot 10^{-23}$ g/cm^3 determined via mass modelling of the Milky Way

- About 1 WIMP in a coffee cup (assuming $m_W \sim 100$ GeV/c^2)

- Circular velocity $v_C = 220$ km/s with radial dispersion velocity $\sigma_r = v_C/\sqrt{2}$.
- Escape velocity $v_{esc} = 544$ km/s determined from the speed of high velocity stars (RAVE)

WIMP velocities

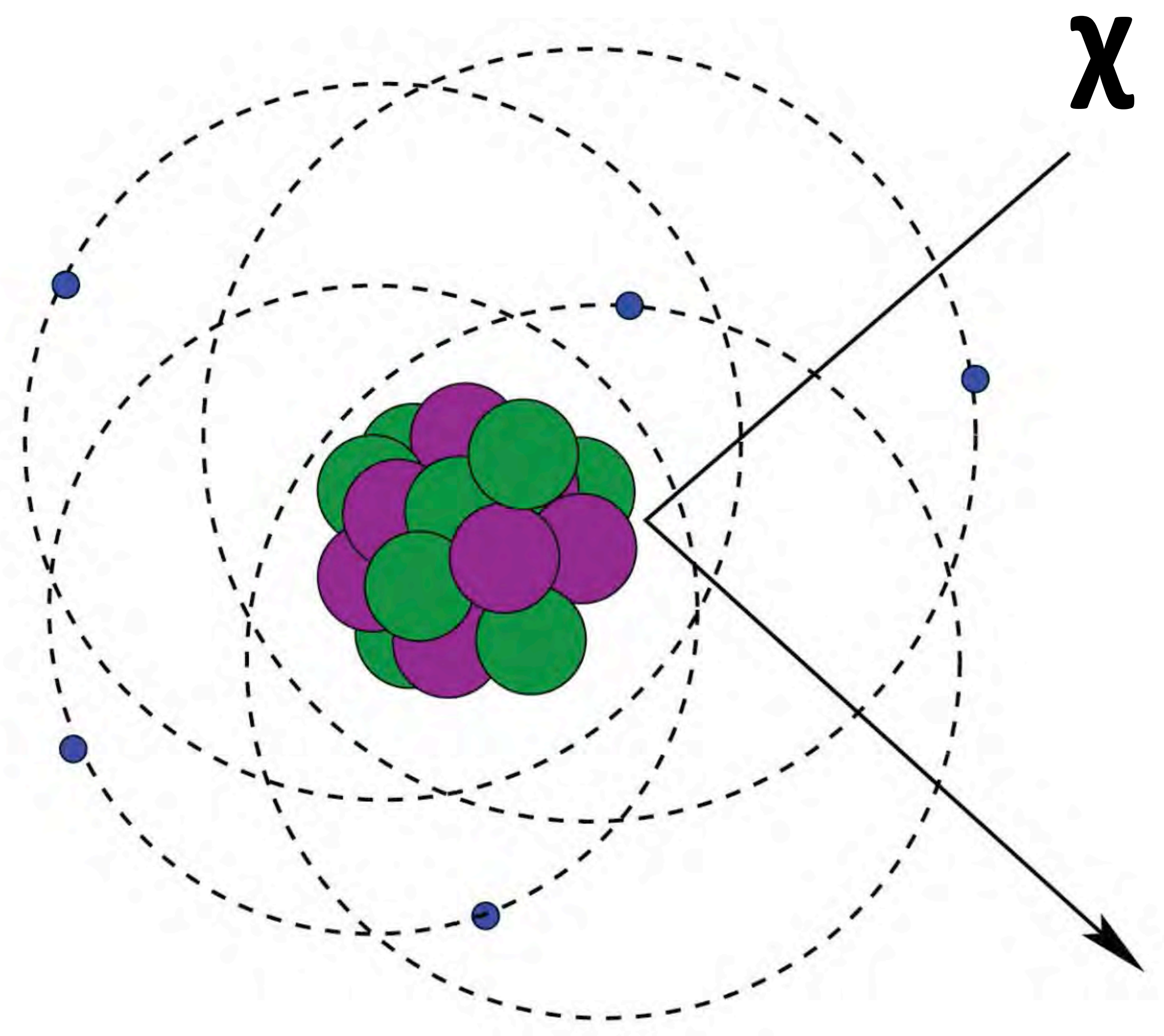
- The velocity distribution of the WIMPs is an essential ingredient
- From cosmological simulations of galaxy formation: **departures from the simplest case of a Maxwell-Boltzmann distribution**
- In direct detection experiments, mostly a simple MB distribution, truncated at v_{esc}, is used in the sensitivity calculation



WIMP direct detection

A simple idea: elastic scattering

(M.W.Goodman & E.Witten, Phys. Rev D 31 (1985) 3059)



ß ~ 0.075

Visible energy

q ~ tens MeV

$$E_R = \frac{q^2}{2M_N} \lesssim 30\text{keV}$$

Observable effect:

- nuclear recoil

but ….

- small energies
- very weak signature

WIMP direct detection

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$

$$\simeq \mathrm{N_N} \frac{\rho_0}{\mathrm{m_W}} \sigma \langle \mathrm{v} \rangle$$

Detector	n_N, E_{th}
Particle/nuclear physics	m_W, σ_W
Astrophysics	ρ_0, f(v)

- Spin-independent interactions: coupling to nuclear mass
- Spin-dependent interactions: coupling to nuclear spin

Scattering cross section

In general, interactions leading to WIMP-nucleus scattering are parameterized as:

- scalar interactions (coupling to WIMP mass, from scalar, vector, tensor part of L)

$$\sigma_{SI} \sim \frac{\mu^2}{m_W^2}[Zf_p + (A - Z)f_n]^2$$

f_p, f_n: scalar 4-fermion couplings to p and n

➡ nuclei with large A favourable (but nuclear form factor corrections)

- spin-spin interactions (coupling to the nuclear spin J_N, from axial-vector part of L)

$$\sigma_{SD} \sim \mu^2 \frac{J_N + 1}{JN}[a_p\langle S_p\rangle + a_n\langle S_n\rangle]^2$$

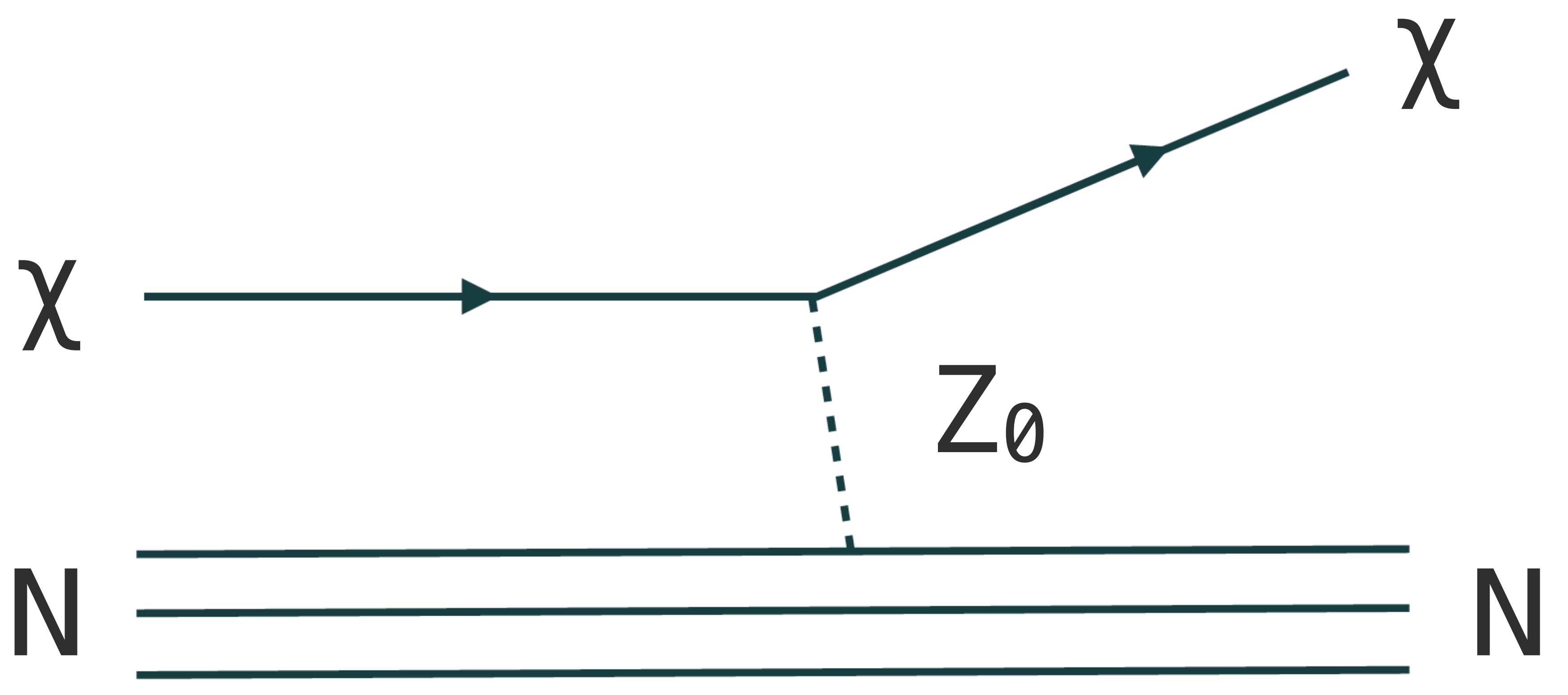
a_p, a_n: effective couplings top and n; $\langle S_p \rangle$, $\langle S_n \rangle$: expectation values of the p and n spins within the nucleus

➡ nuclei with non-zero angular momentum (corrections due to spin structure functions)

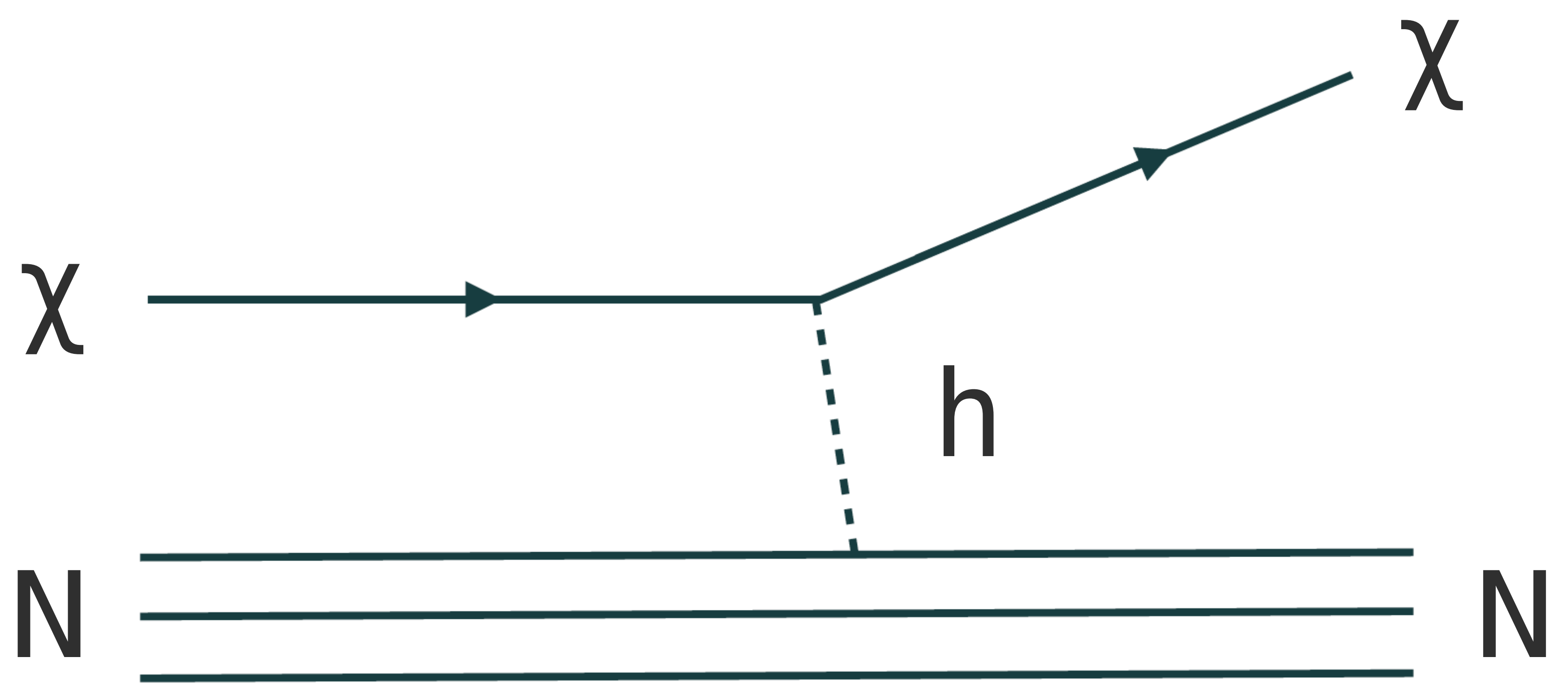
Particle physics

- Typical cross section examples:

➡ $\sigma_0 \sim 10^{-39}$ cm^2



➡ $\sigma_0 \sim 10^{-47}$-10^{-44} cm^2

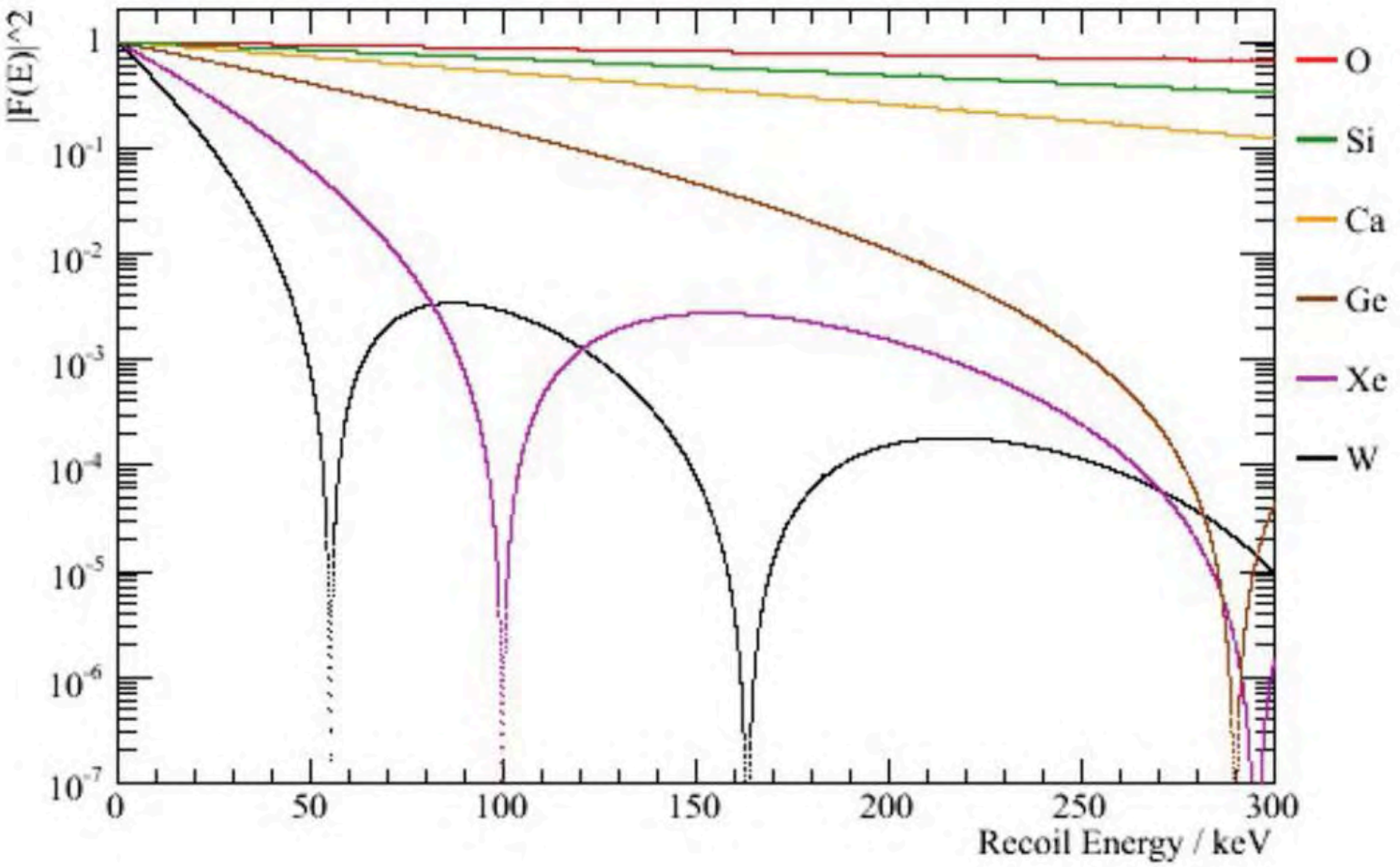


Nuclear form factors

- Nucleons are bounded to a nucleus. Under proper conditions the WIMP scattering is coherent with all the nucleus components. A detailed description of the process is mandatory.
- This is generally treated in terms of a correction factor or form factor.
- With the Helm parametrization for the nuclear density the form factor is

$$F^2(Q) = [\frac{3j_1(qR_1)}{qR_1}]^2 e^{-(qs)^2}$$

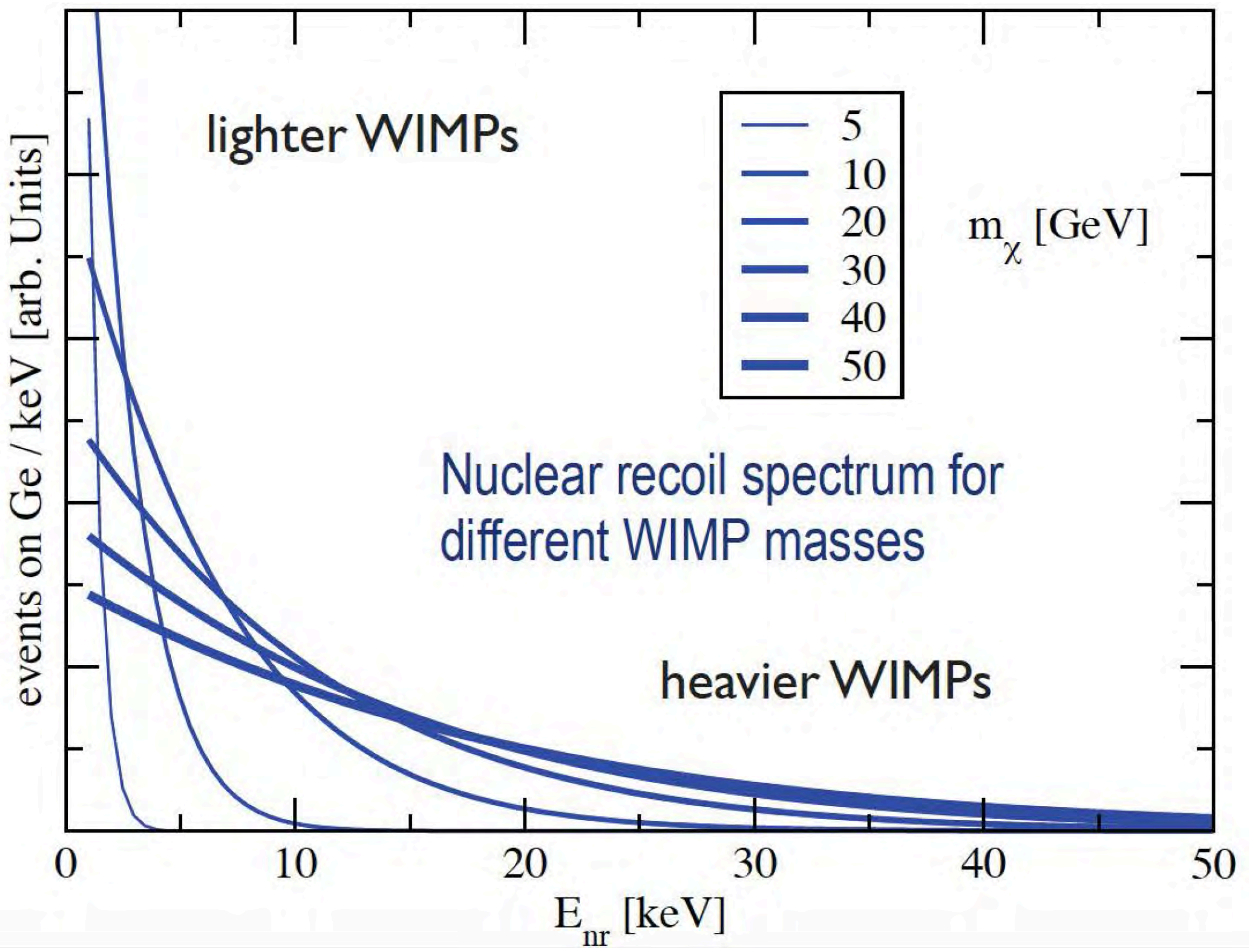
j_1 = 1st Bessel function
s = nuclear skin thickness ~ 1 fm
$R_1 \propto 1.14\ A^{1/3} \sim 7\ A^{1/3}\ GeV^{-1}$



- While coherence favors large nuclei, form factor is important for large nuclei (Xe, W, etc.)
- For these targets, a low energy threshold is essential to minimize Form factor suppression of rate

Interaction rates

- Integrate differential rates $$R \sim 0.13 \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$



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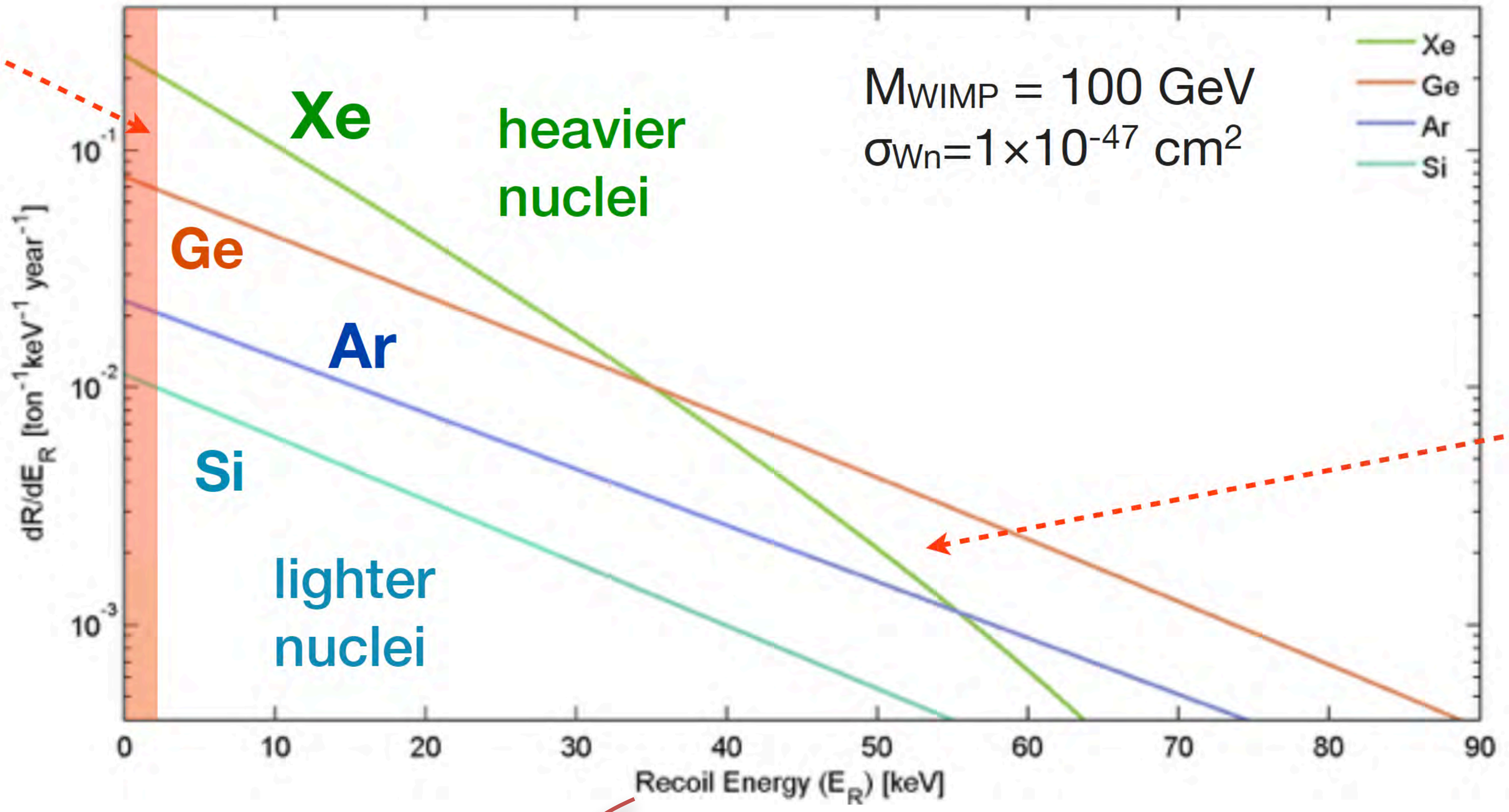
$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu^2}}$$



Rate and shape of recoil spectrum depend on target material

$F^2(E_R)$: nucleons are bound in a nucleus

E_R is the recoil energy but detectors measure $E_{electron}$

Dark matter signatures: annual modulation

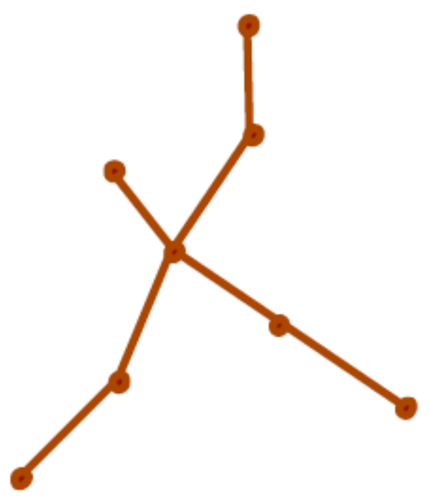
- The earth follows the Sun in the direction of Cygnus

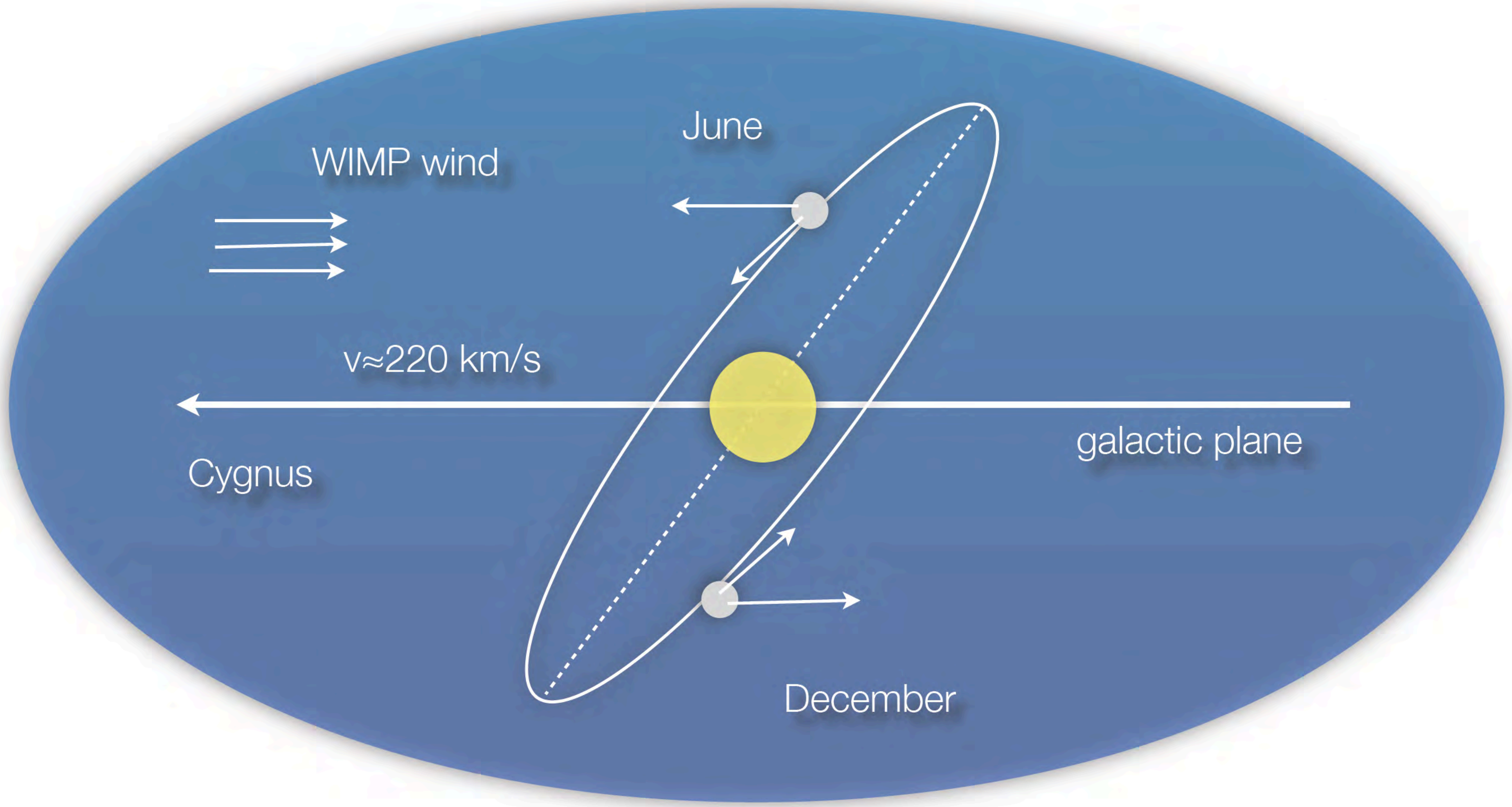
➡ the earth revolutionary motion causes
  - annual event rate modulation: June - December asymmetry ~ 2-10%
  - sidereal directional modulation: asymmetry ~20-100% in forwardbackward event rate

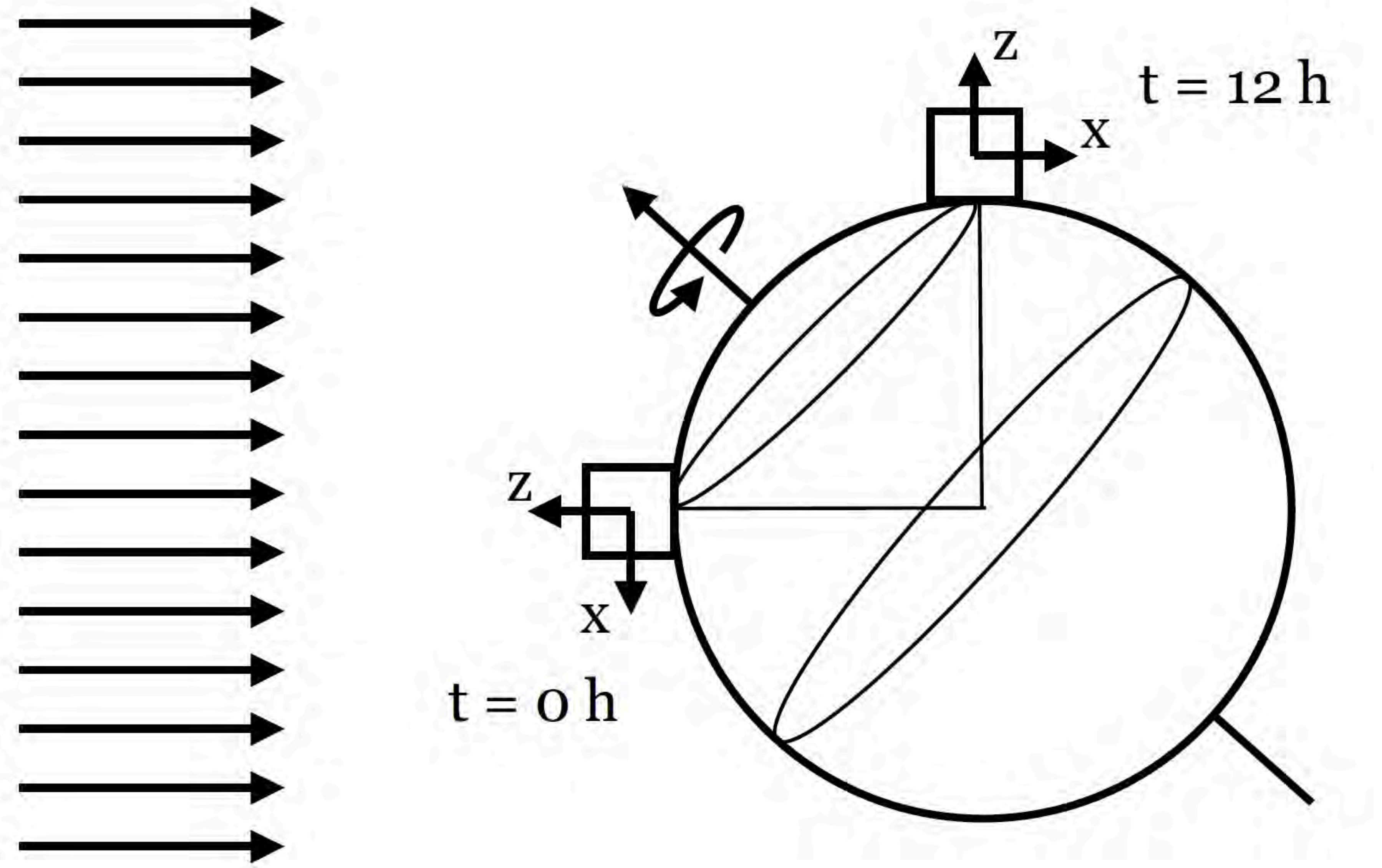
$$\frac{dR}{dE}(E,t) \sim S_0(E) + S_m(E) \cdot cos(\frac{2\pi(t-t_0)}{T})$$

the relative speed (and the rate) of DM particles is larger in summer

Cygnus





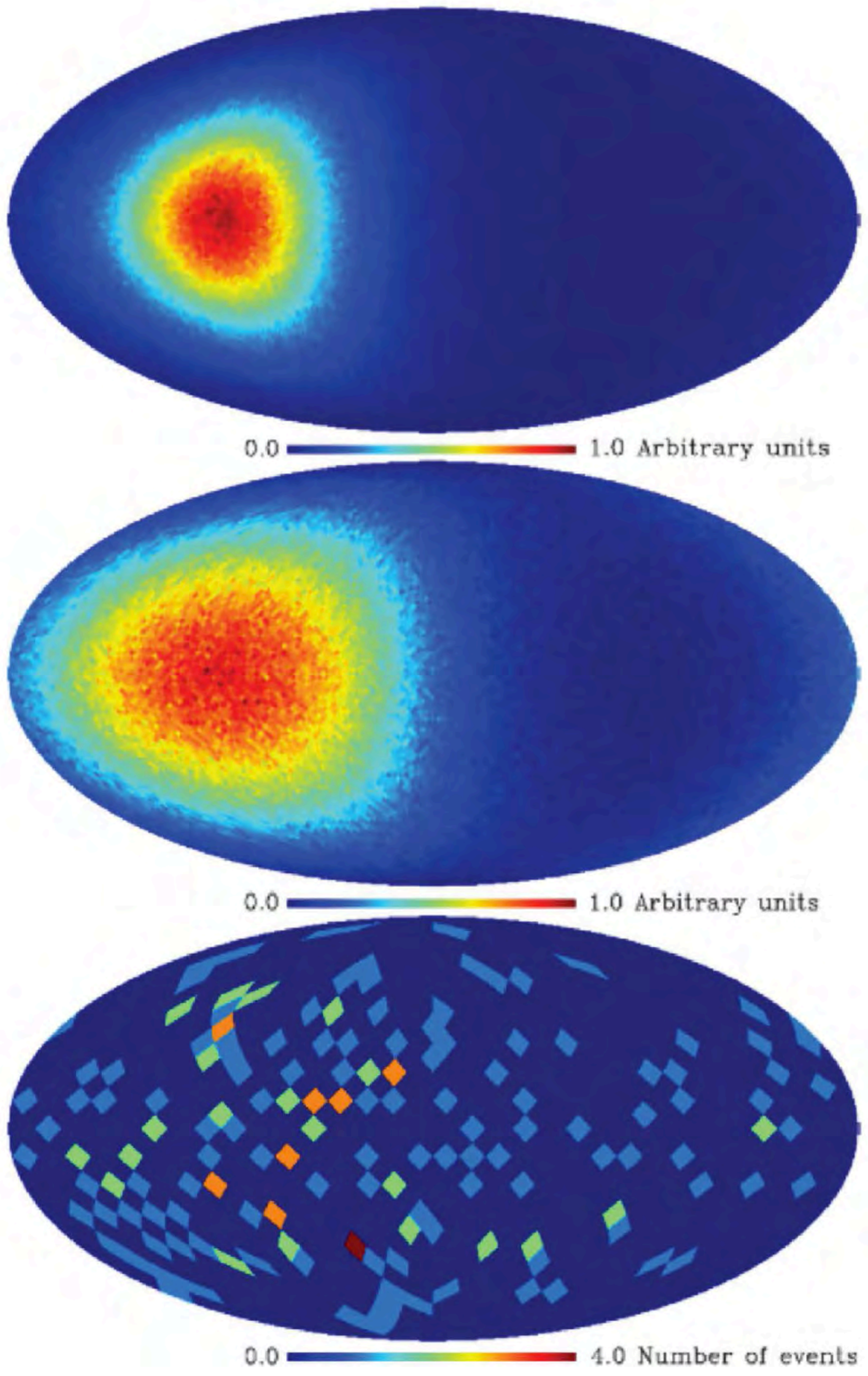


Dark matter signatures: directionality

Average WIMP direction is opposite to the motion of the sun towards Cygnus

$$\frac{dR}{dE d\cos\gamma} \propto \exp\left[\frac{-[(v_E + v_\odot)\cos\gamma - v_{min}]^2}{v_C^2}\right.$$

- **γ :** NR direction relative to the mean direction of solar motion
- **v_E and $v_\odot$:** the Earth and Sun motions
- **$v_C = \sqrt{3/2}\, v_0$:** halo circular velocity



- WIMP flux in the case of an isothermal spherical halo
- WIMP-induced recoil distribution
- A typical simulated measurement:
  - 100 WIMP recoils and
  - 100 background events (low angular resolution)

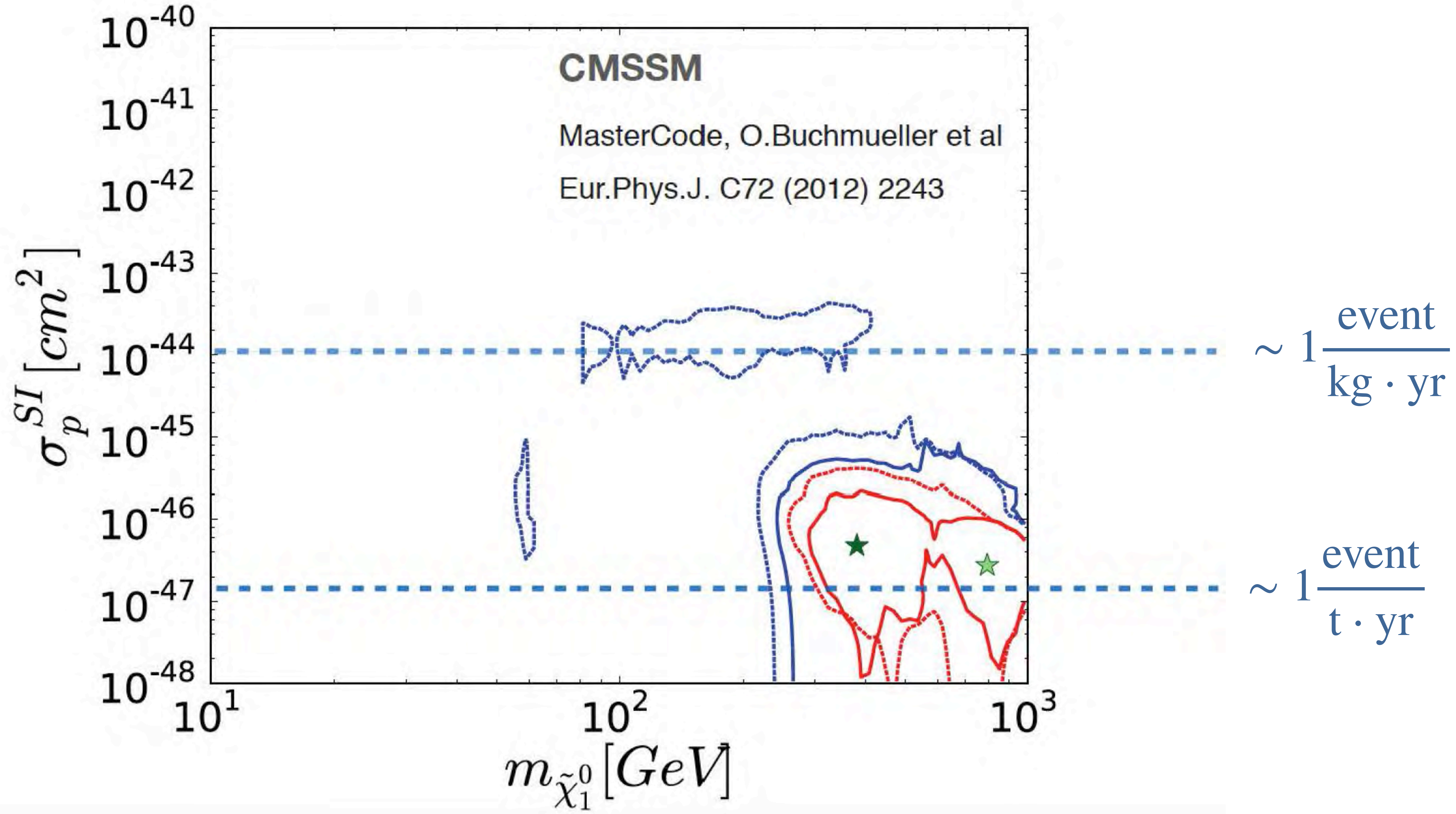
Experiments

Requirements for a dark matter detector

- Large detector mass
- Low **energy threshold** ~ sub-keV to few keV's
- Very **low background** and/or background discrimination
- Long term stability

Possible signatures of dark matter

- Spectral shape of the recoil spectrum
- Annual modulated rate
- Directional dependance



How to deal with background?

External γ's from natural radioactivity:

- Suppression via self-shielding of the target
- Material screening and selection
- Rejection of multiple scatters & discrimination

Neutrinos: from the Sun, atmospheric and from supernovae.

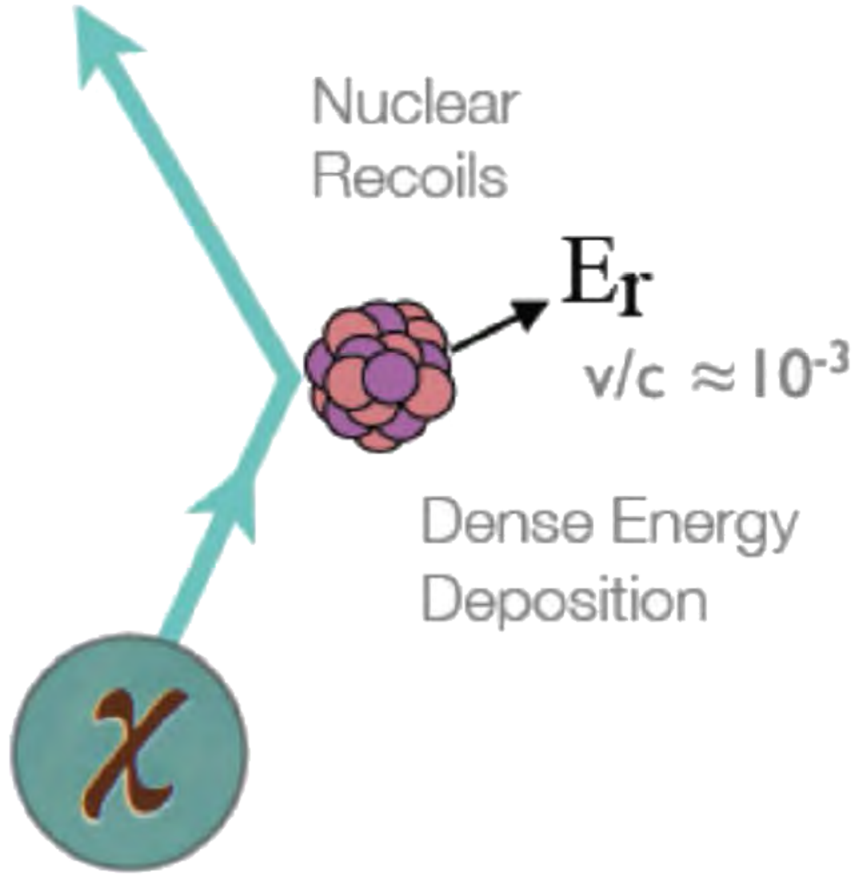
- Elastic neutrino-electron scattering
- Coherent neutrino-nucleus scattering

External neutrons: muon-induced, (a, n) and from fission reactions

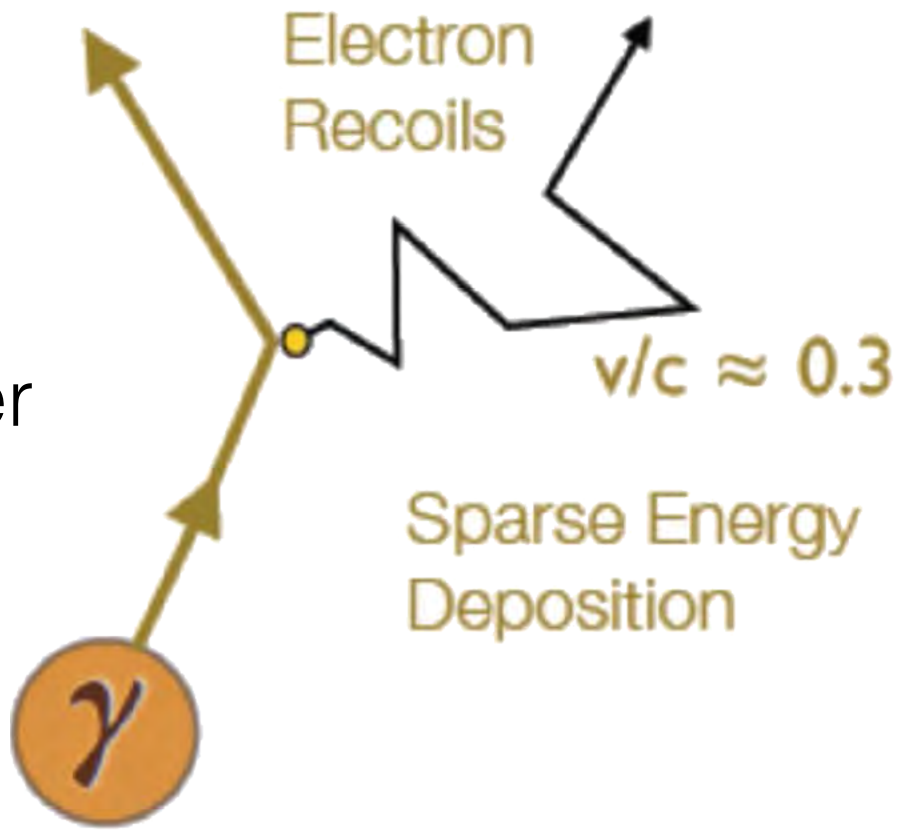
➡ go underground!

➡ shield: passive (polyethylene) or active (water/scintillator vetoes)

➡ material selection for low U and Th contaminations



- WIMPs and neutrons scatter off the atomic nuclei
- Phototns and electrons scatter off atomi electrons



Possible strategies?

- **Reduction**
- **Identification (selection)**

Background reduction

Deep underground laboratory

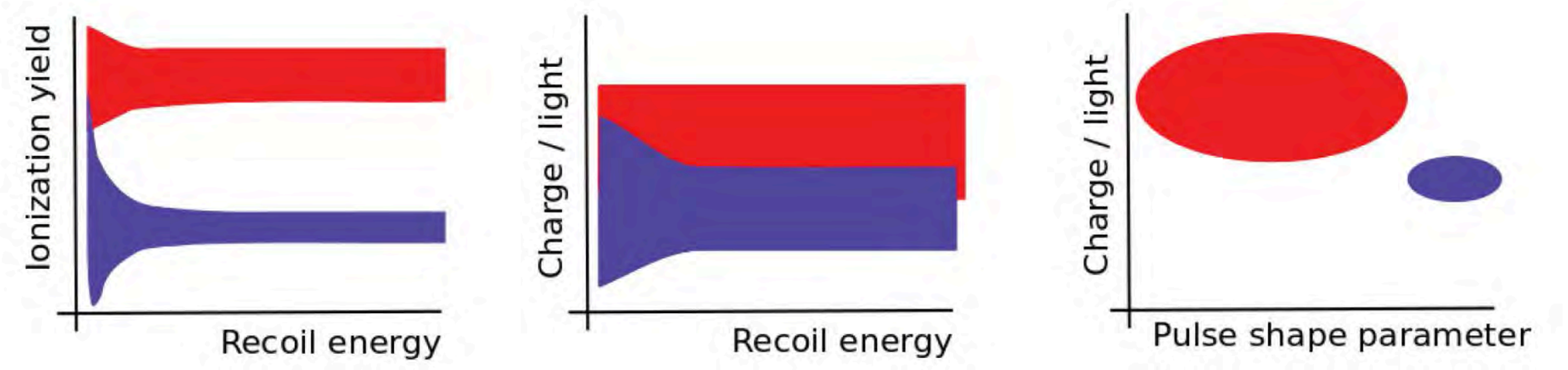
Heavy radiation shields

Select low-activity materials

- WIPP in USA (DMTPC)
- LSBB in France (SIMPLE)
- Kamioka in Japan (XMASS,NEWAGE)
- Soudan in USA (SuperCDMS,GoGeNT)
- Y2L in Corea (KIMS)
- Boulby in UK (DRIFT,ZEPLIN)
- LNGS in Italy (XENON,DAMA,Cresst,DarkSide)
- LSM in France (Edelweiss, MIMAC)
- SURF in USA (LUX)
- SNOLAB in Canada (DEAP/CLEAN,PICASSO,COUPP)
- Jin-Ping in China (PandaX,CDEX)

Detectors

- stability: monitoring of detector parameters (amplification of signals, slow control parameters, ..) and of the related electronics
- energy scale: detector signals are photoelectrons, charges or heat → **need to convert to keV_{nr}**
- signal discrimination: description of nuclear and electronic recoil regions

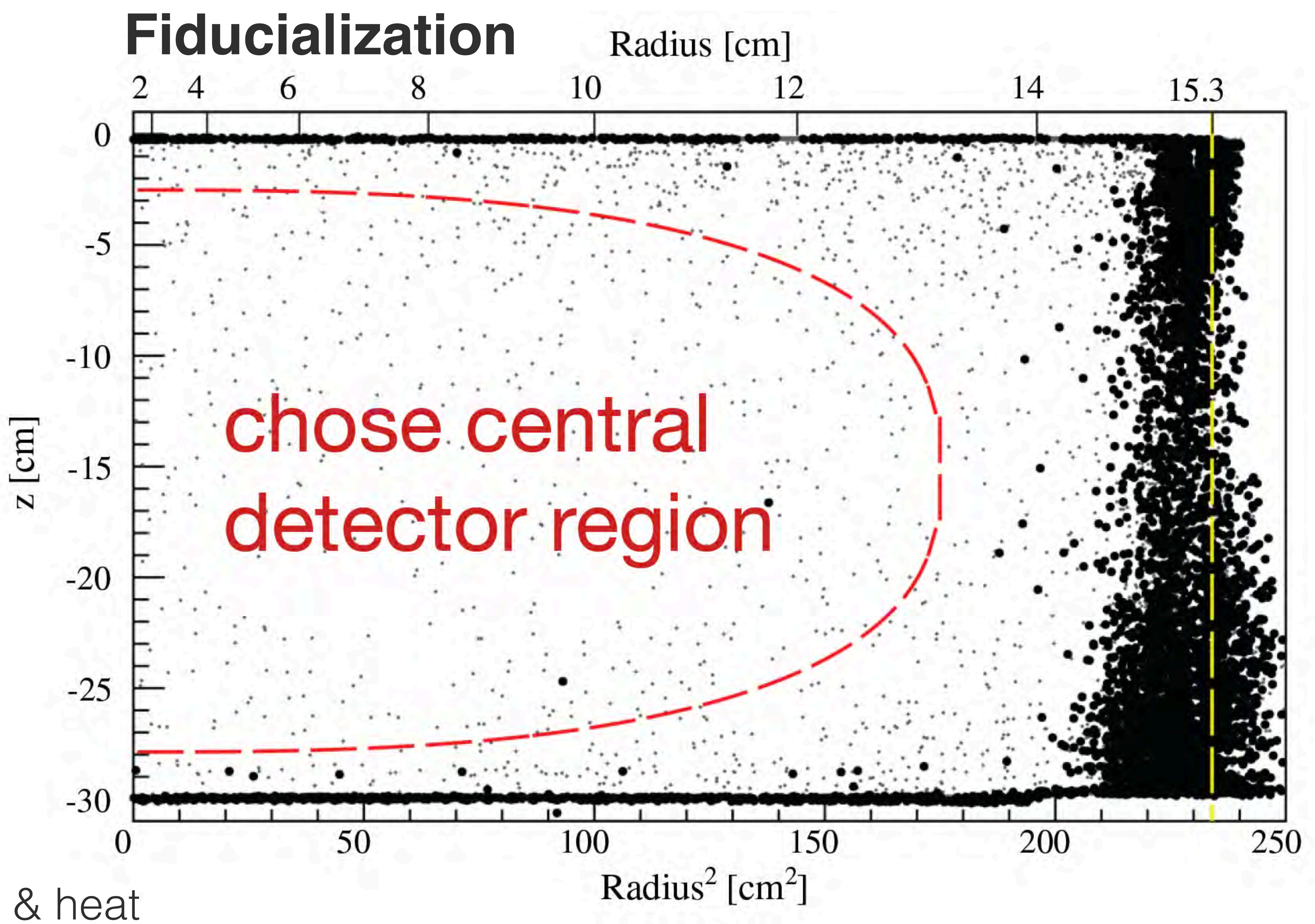


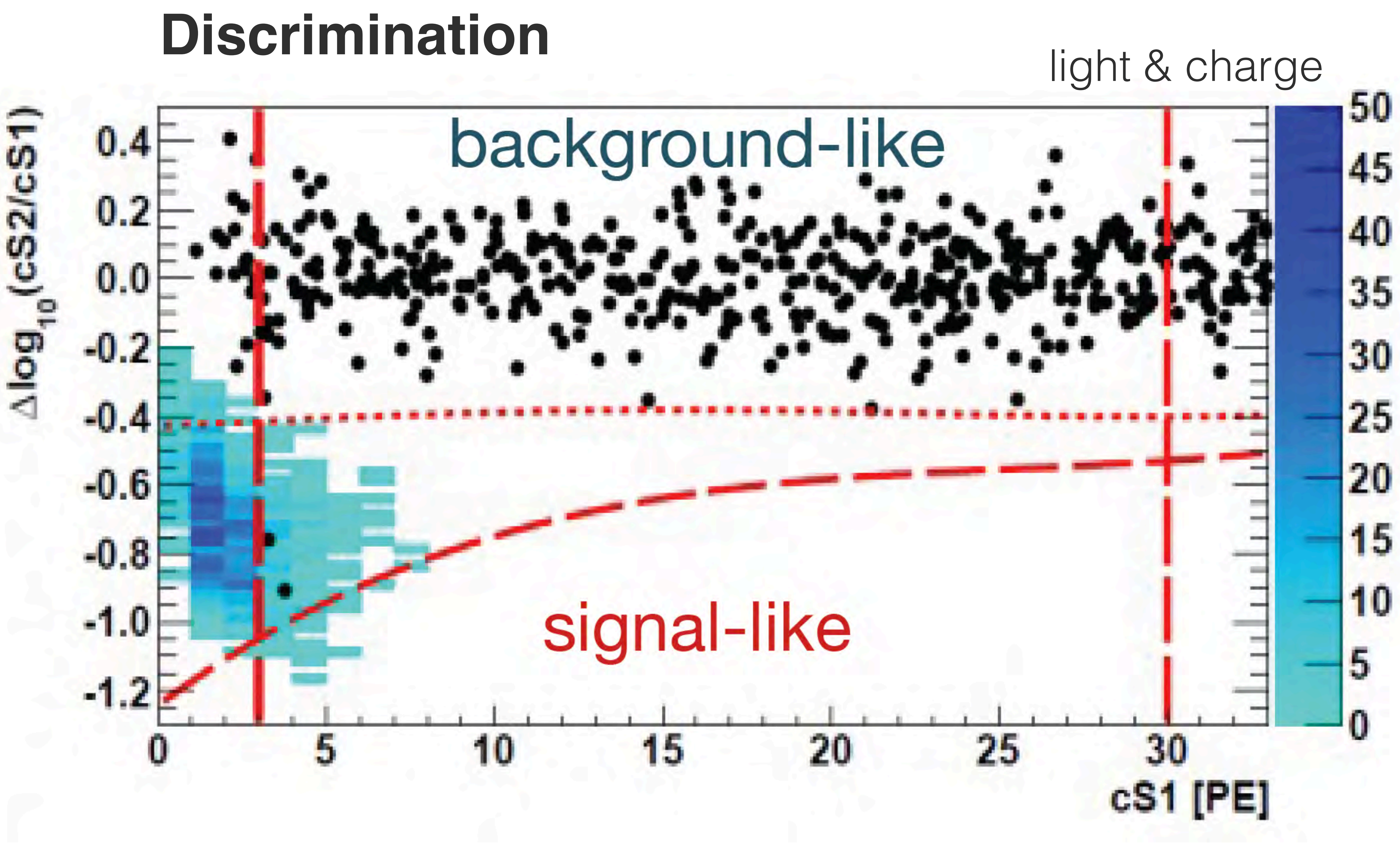
discrimination depends on the experimental technique:

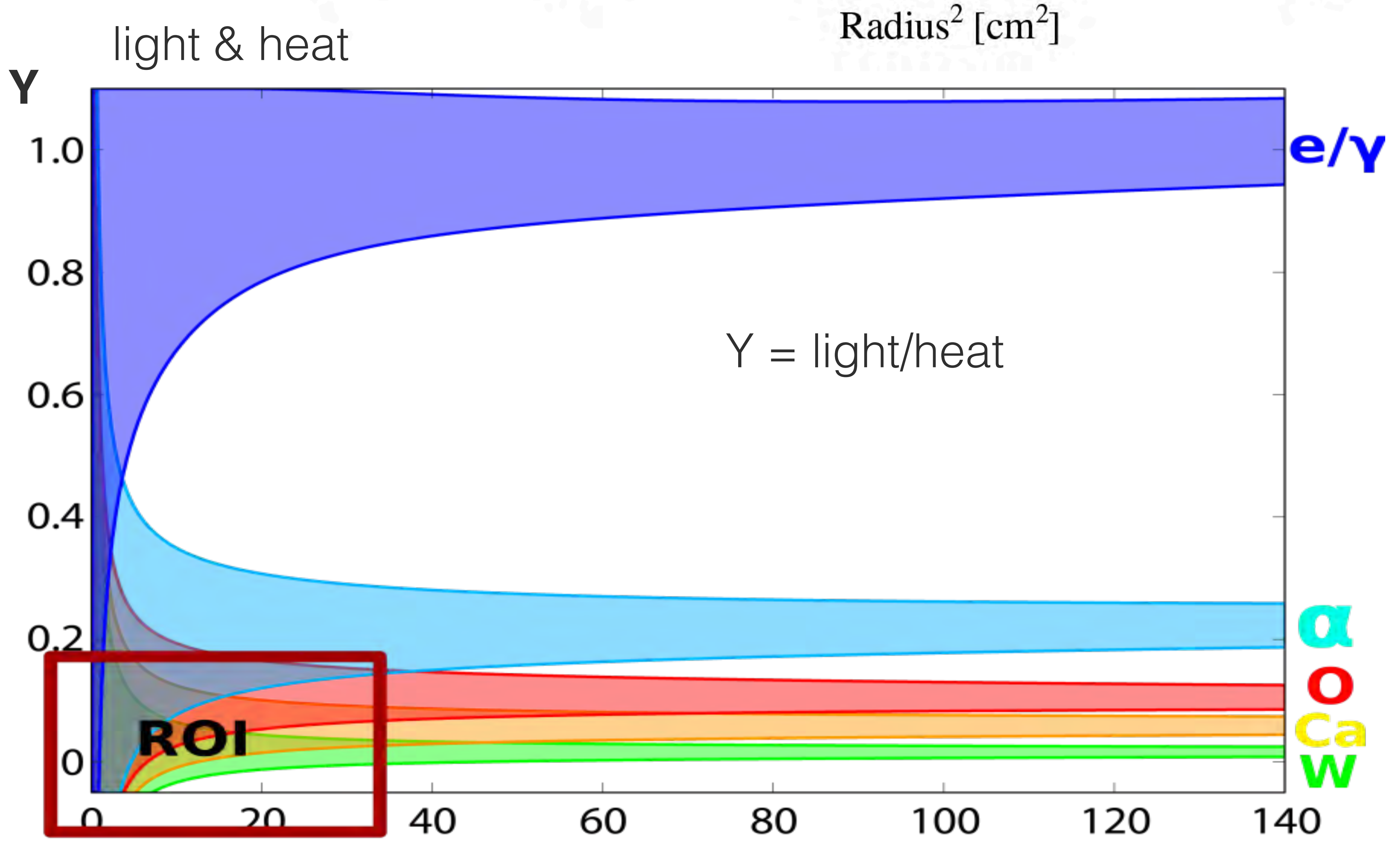
- cryogenic germanium detector (left): ionization or light yield (no surface events included)
- liquid xenon detector (middle): charge to light ratio
- liquid argon detector (right): charge to light ratio and signal shape

Background discrimination

- Collect as much as possible information
  - topology
  - charge
  - light
  - heat (phonons)
- and combine them



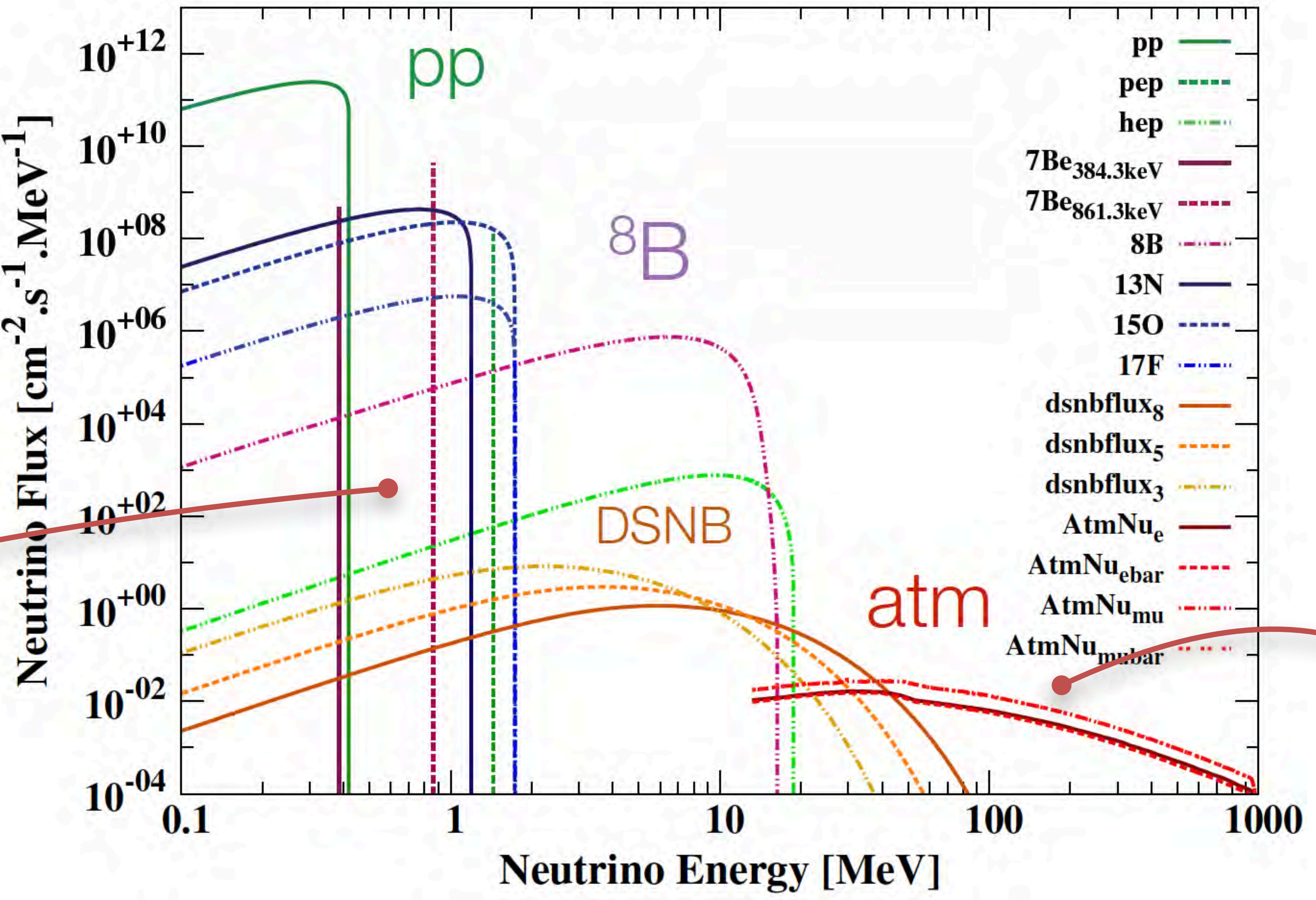




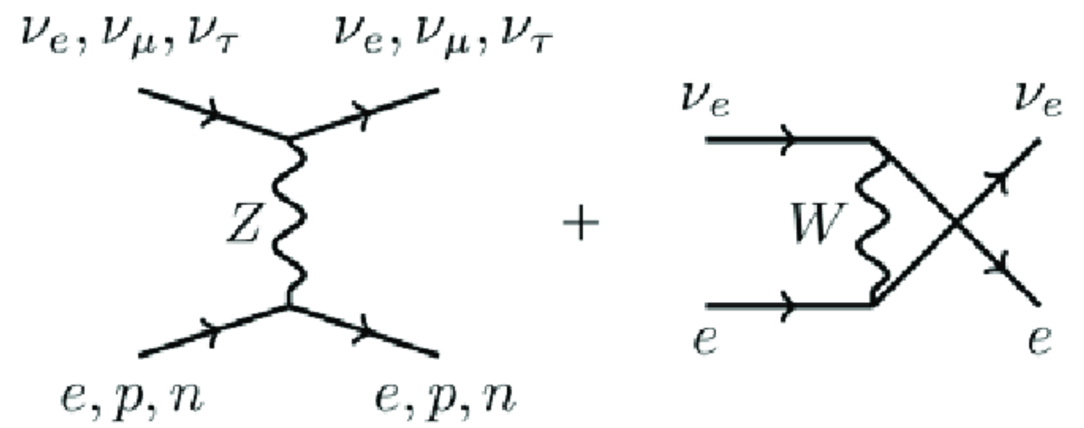
Neutrino background

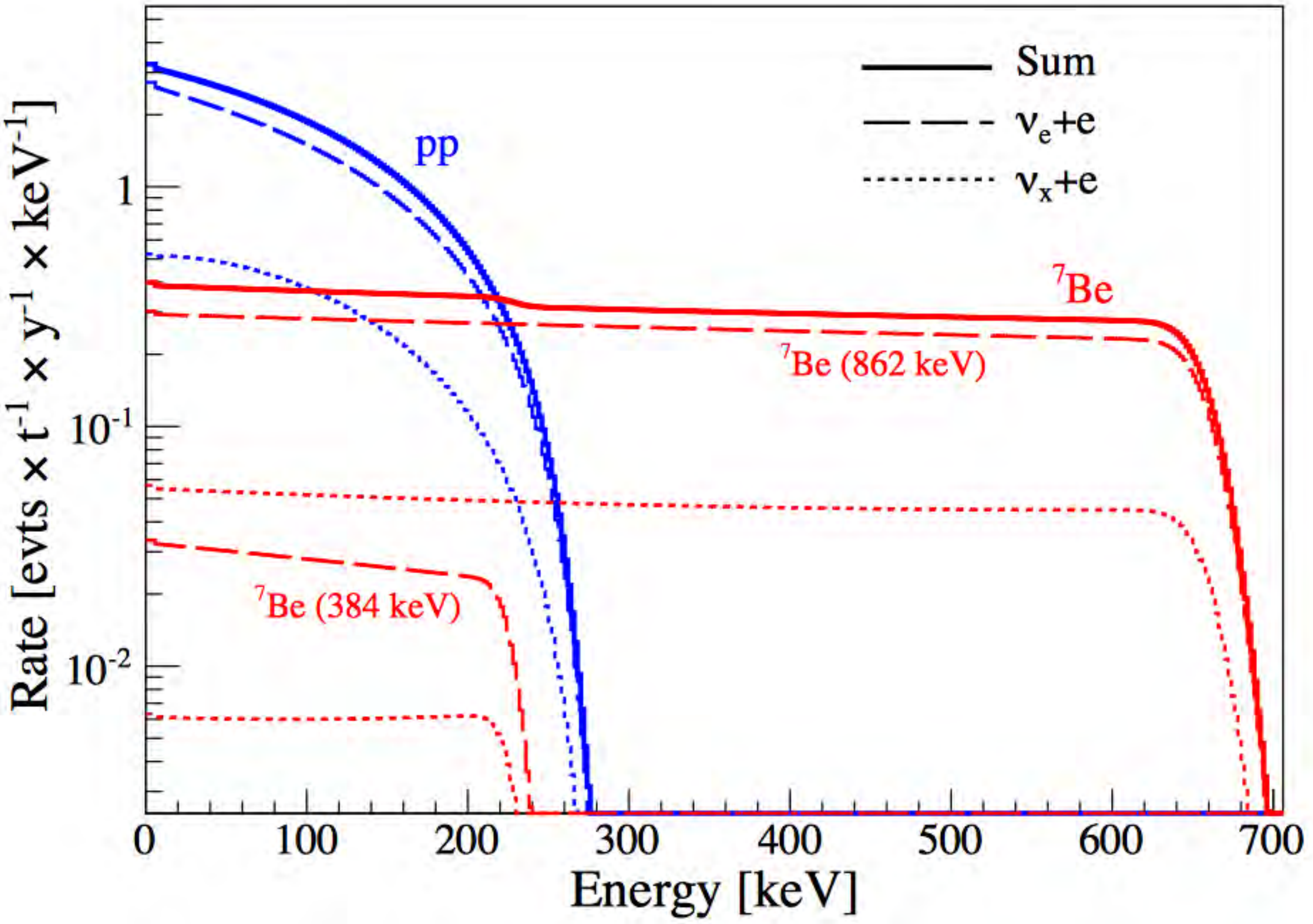
- Neutrinos (solar, atmospheric and supernovae) are the ultimate (unavoidable) background

Fluxes

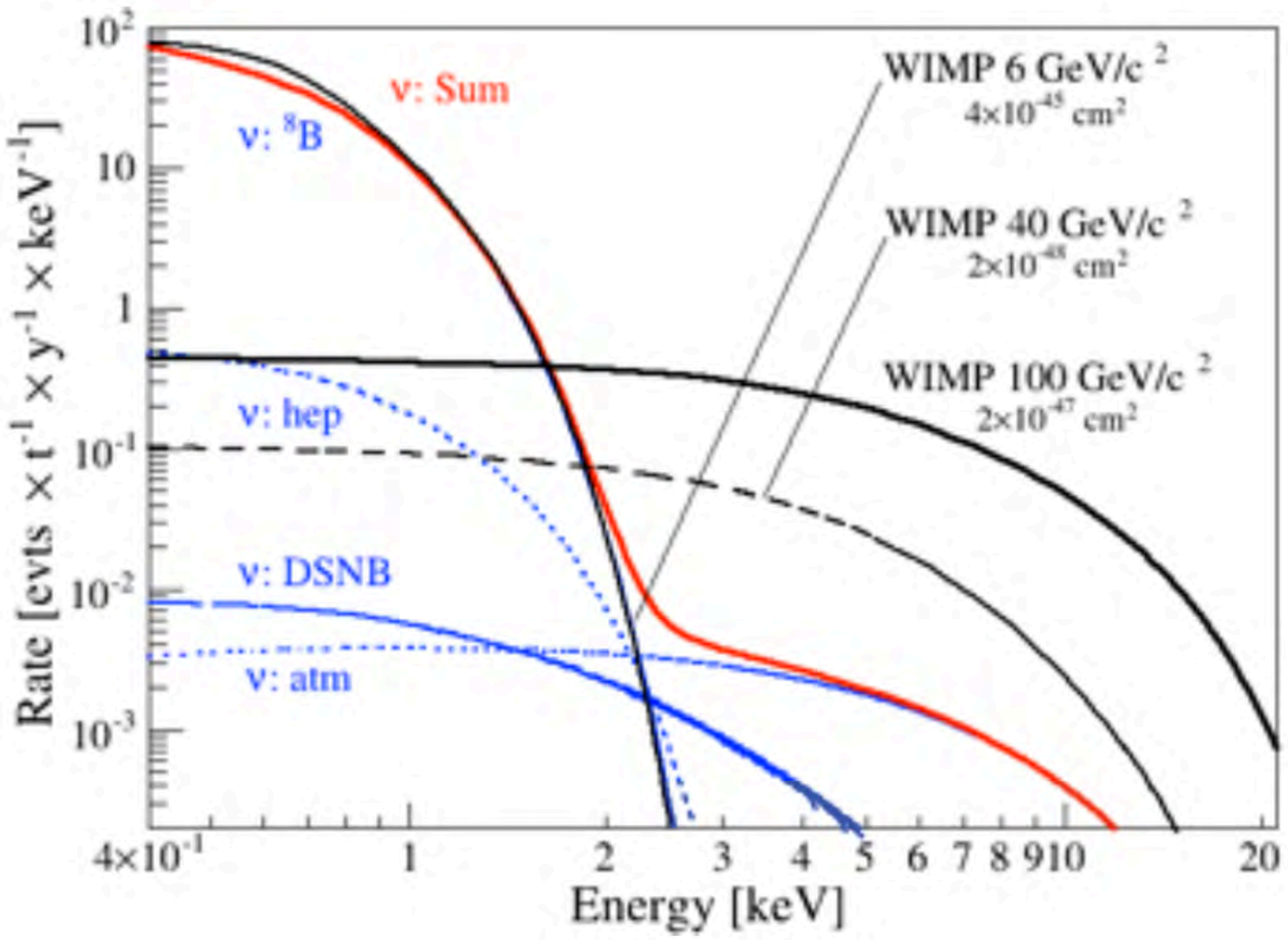


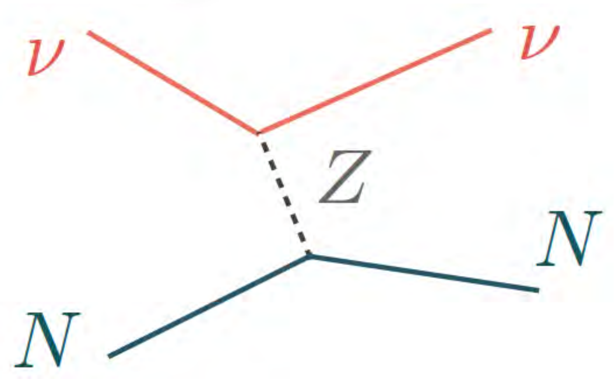
electron scattering





nuclear scattering





Sensitivity plots

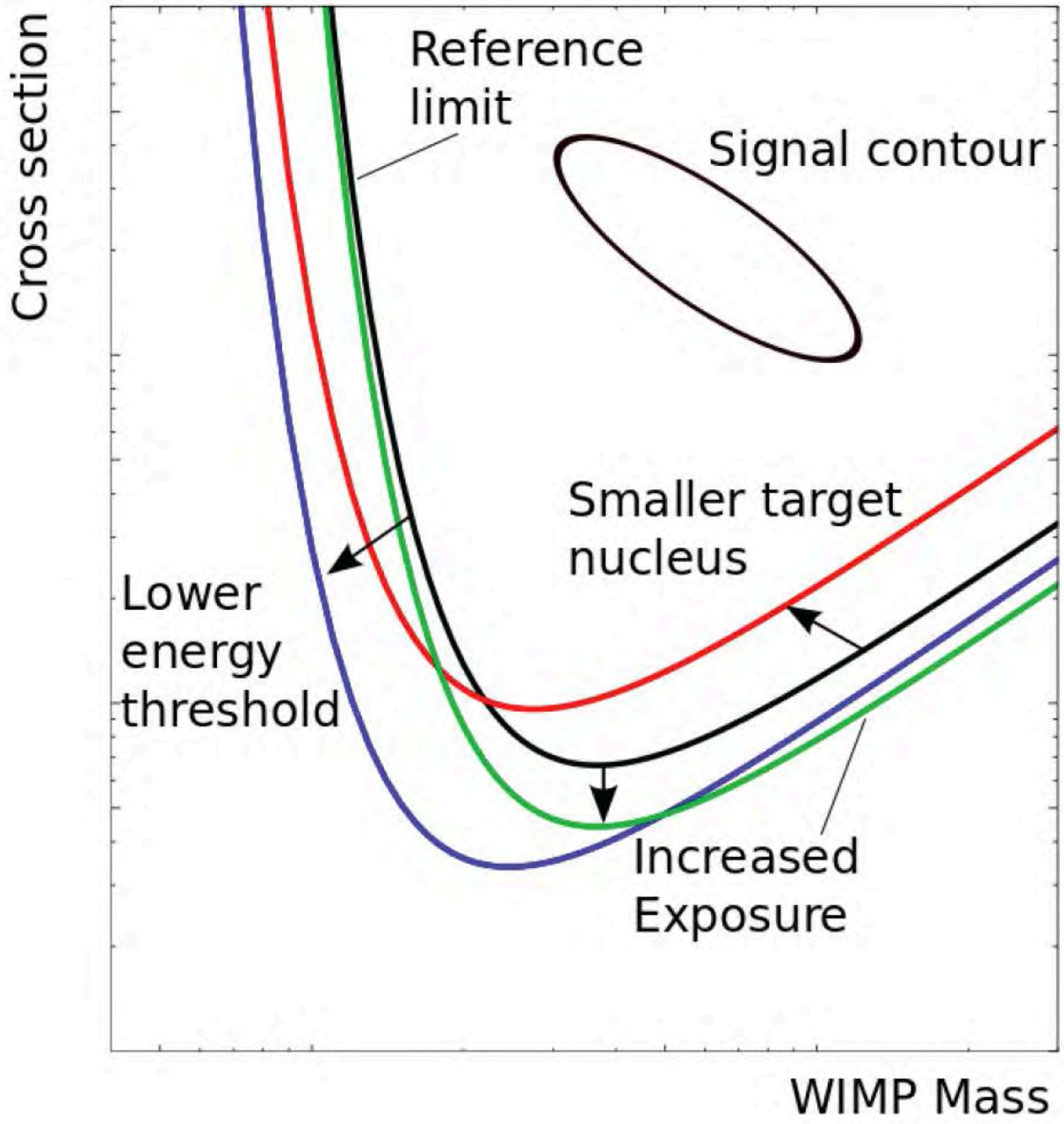
data analysis: compare expected signal with energy spectra of selected events

Positive signal

- Region in σx versus mx

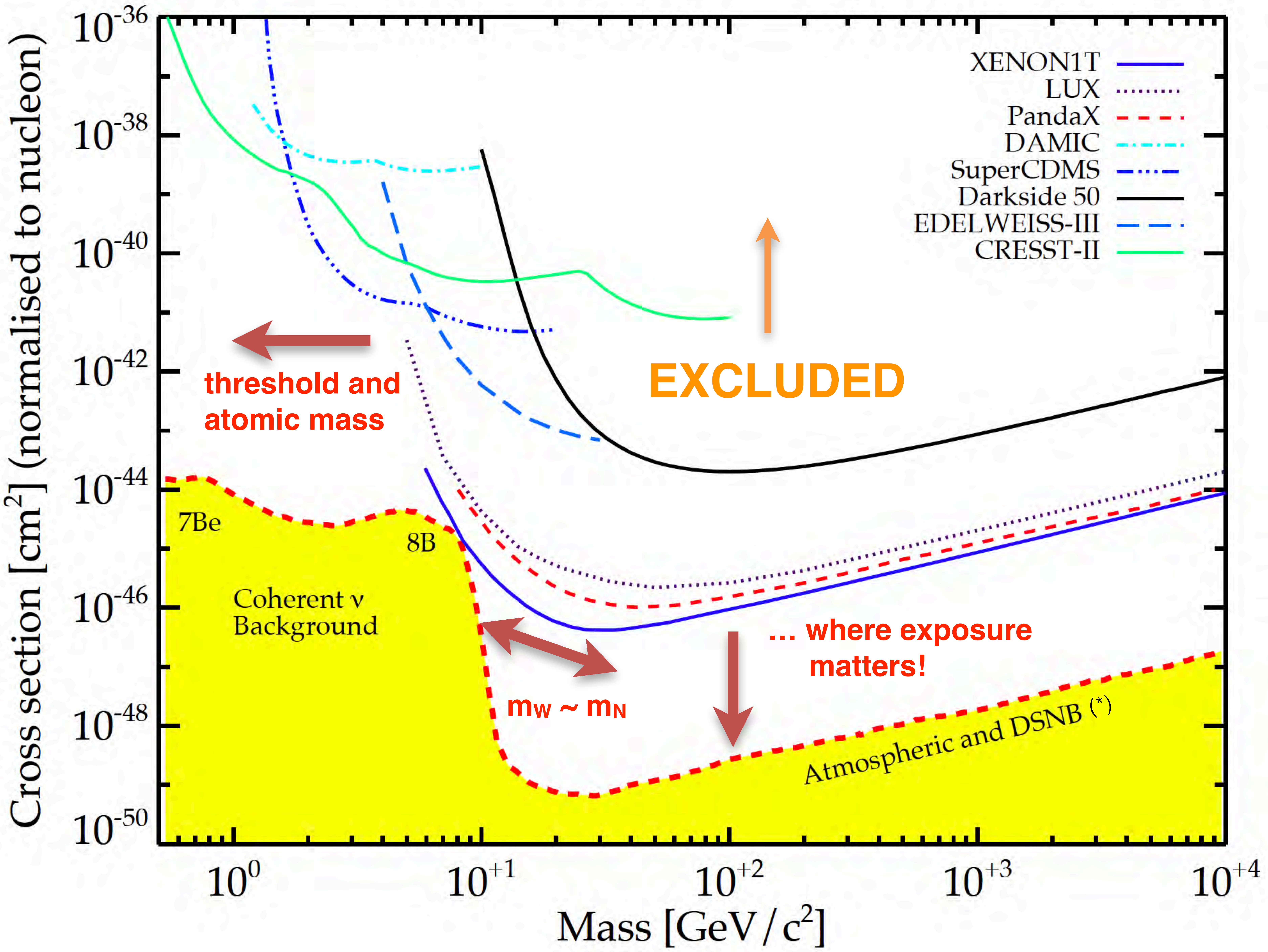
Zero signal

- Exclusion of a parameter region
- Low WIMP masses: detector threshold matters
- Minimum of the curve: depends on target nuclei
- High WIMP masses: exposure matters E = m·t



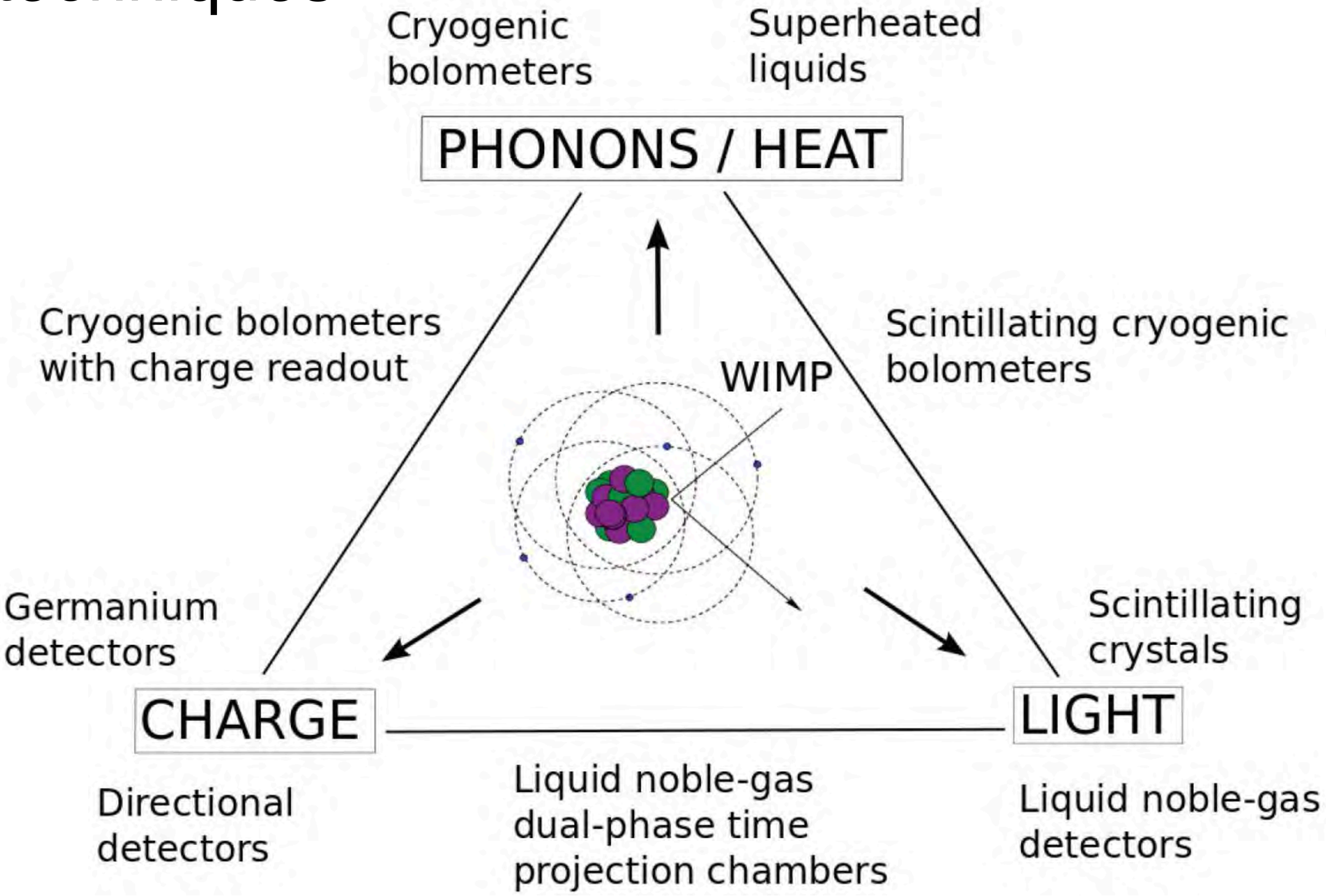
Global view

- A probably outdated but very instructive plot



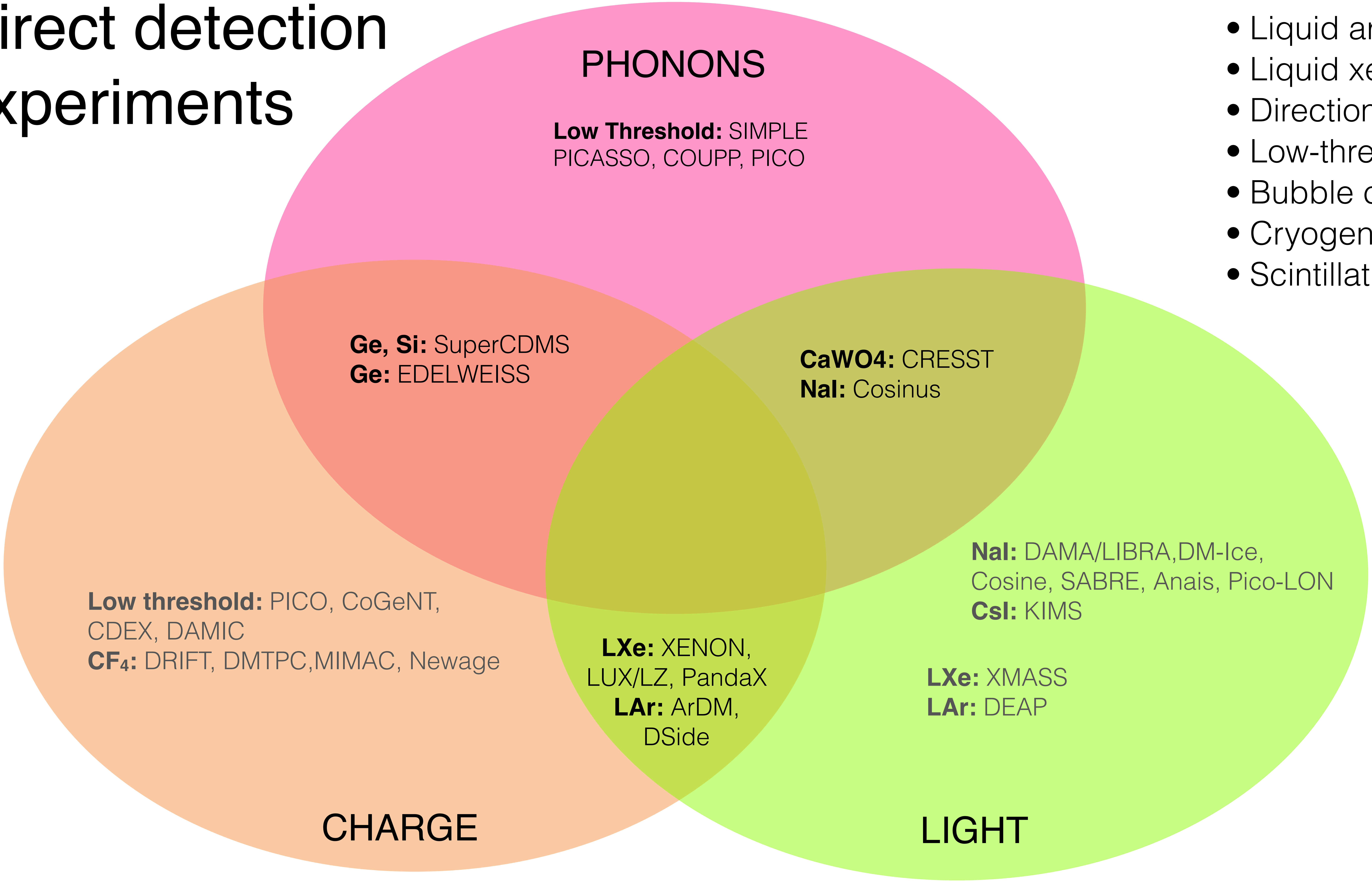
(*) DSNB = Diffuse Supernova Neutrino Background = weak glow of MeV neutrinos and antineutrinos from distant core-collapse

Detection techniques



J. Phys. G43 (2016) 1, 013001 & arXiv:1509.08767

Direct detection experiments

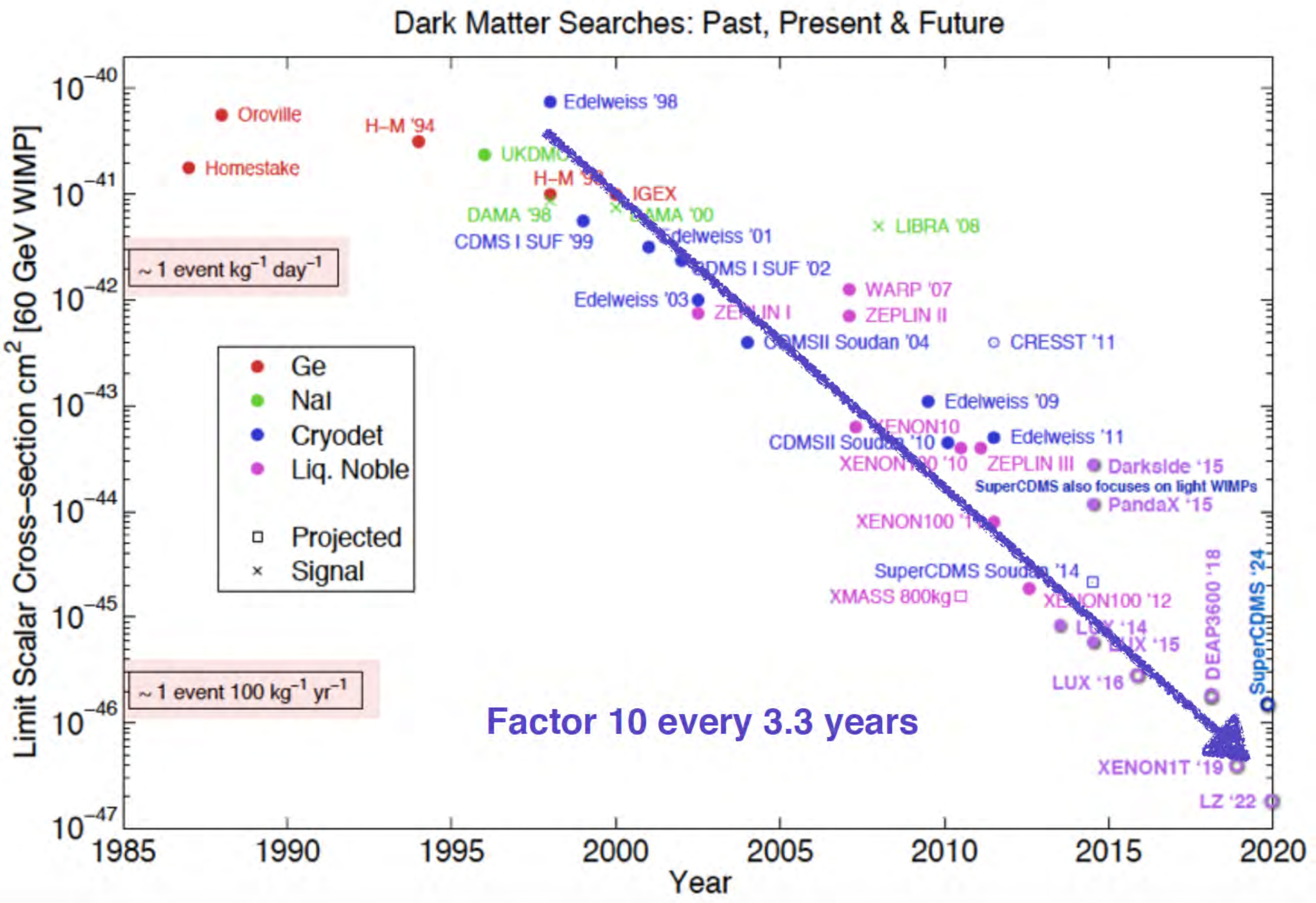


- Liquid argon
- Liquid xenon
- Directional detectors
- Low-threshold
- Bubble chambers
- Cryogenic bolometers
- Scintillating crystals

International competition

Very competitive field with rapid progress:

- detector sensitivity improved by ~5 orders of magnitude in the last 20 years



Experiments summary

Liquid Noble targets:

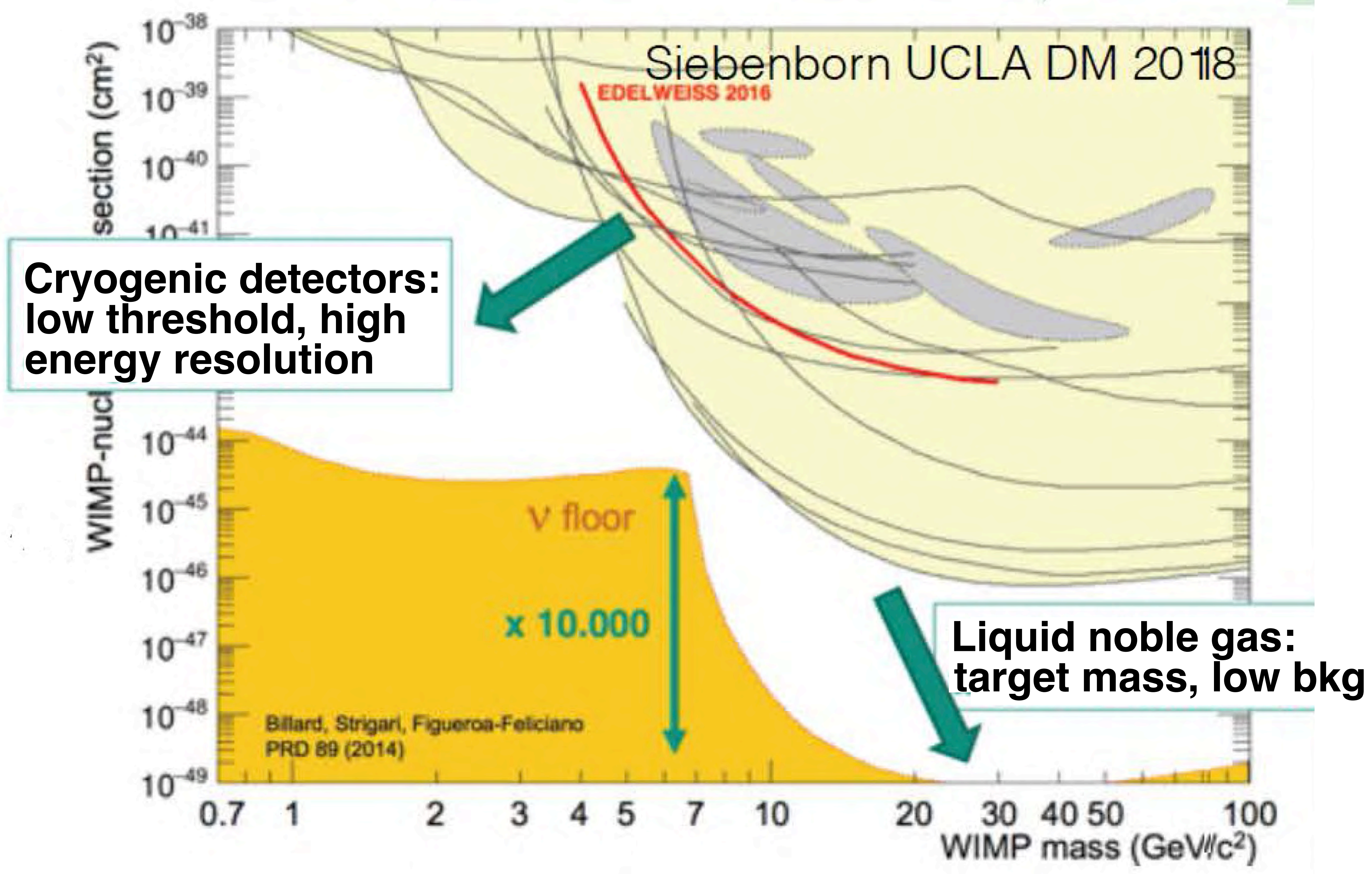
- Largest and most sensitive over the widest WIMP range
- **5 GeV-1 TeV WIMP masses probed**
- Darkside, DARWIN, DEAP3600, LUX, LZ, Panda-X, XENON1 T, XENONnT 1

Cryogenic crystal targets:

- Oldest technology, with new innovations
- **1-10 GeV WIMP masses probed**
- CRESST, EDELWEISS, SuperCDMS,COQ

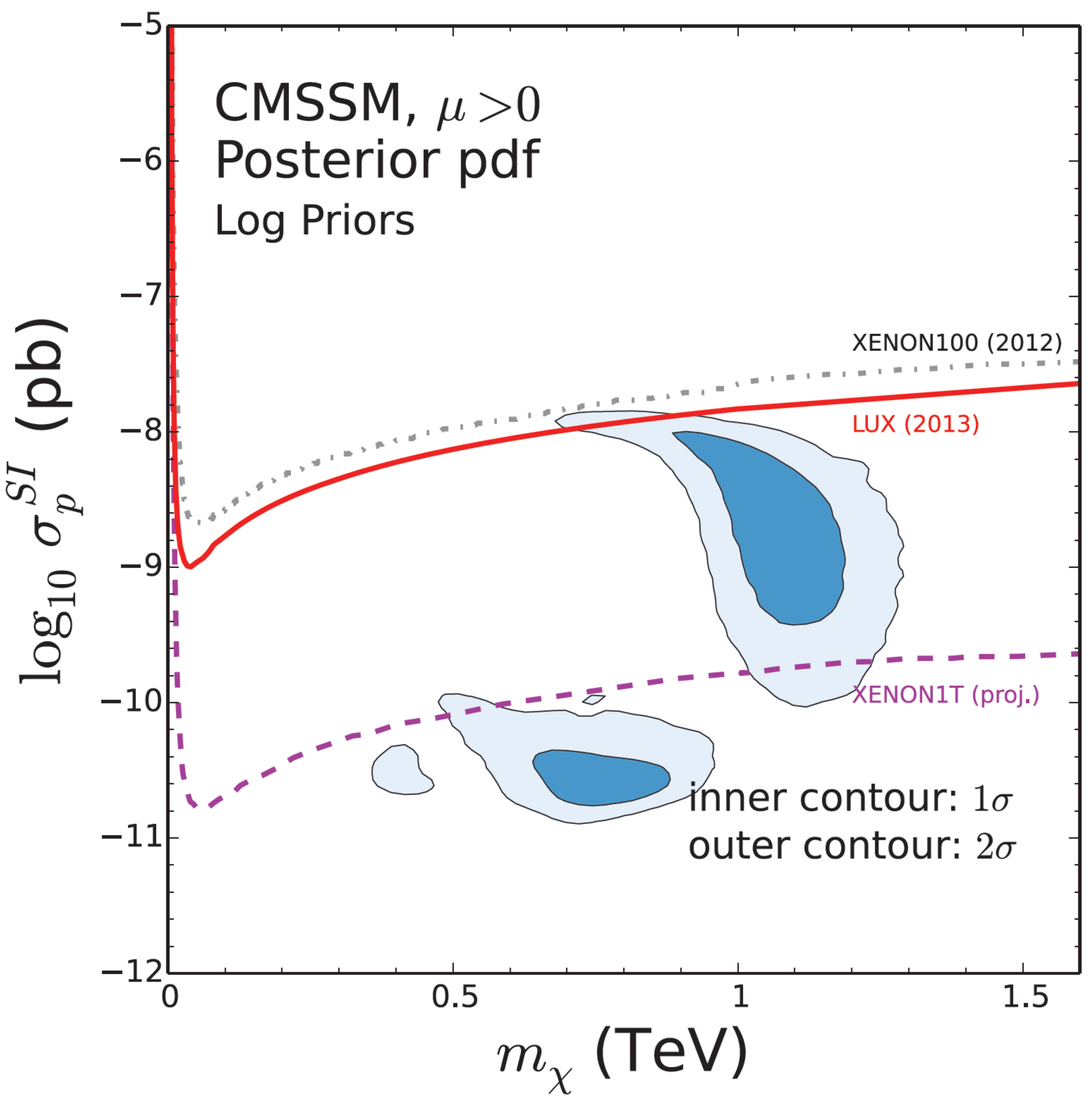
Alternate targets with unique properties:

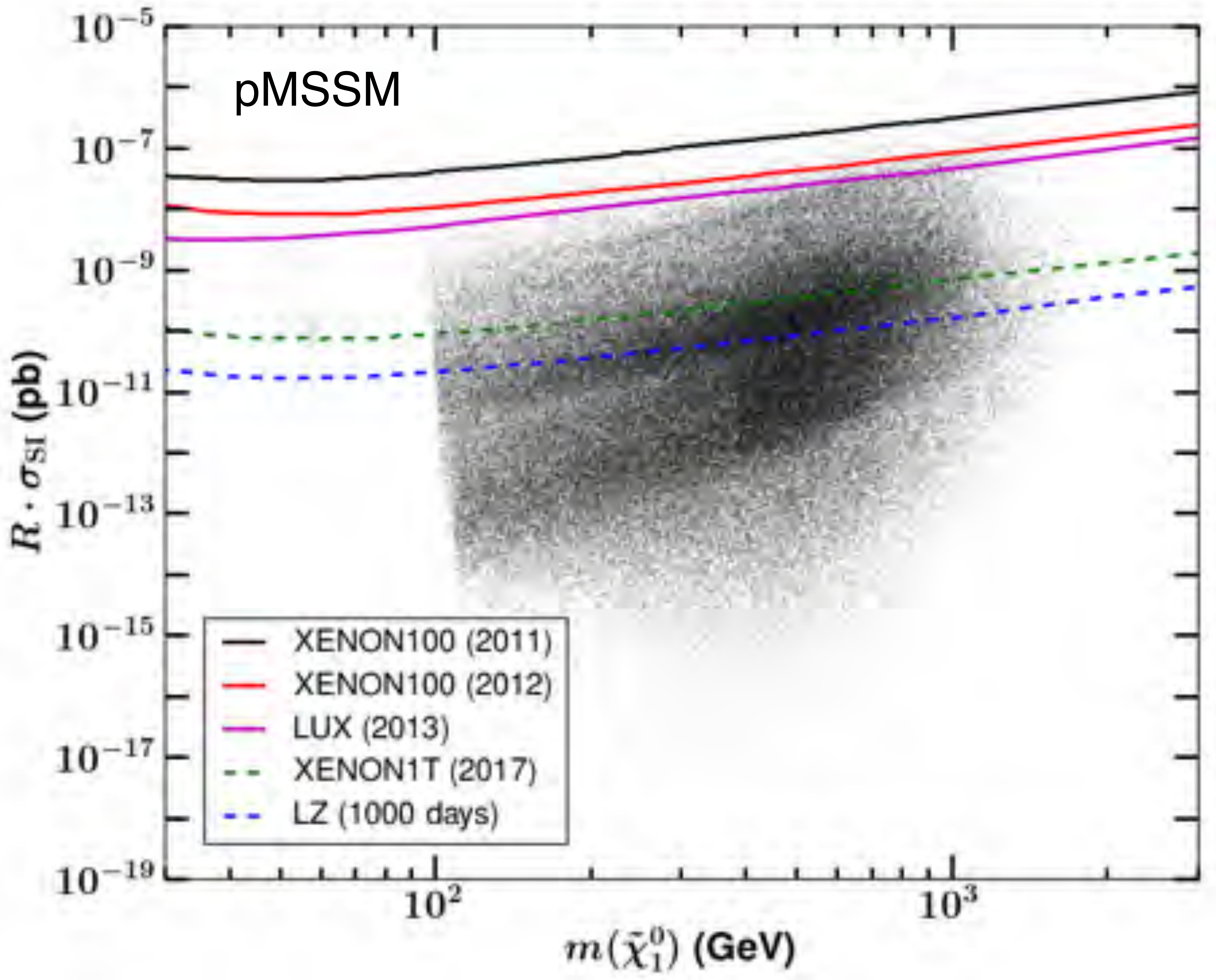
- NaI crystals, bubble chambers
- ANAIS, COSINE, DAMA/LIBRA, SABRE, PICO



SUSY Predictions

- Supersymmetric theories (and experimental measurements) limit the available parameter space





Annual modulation: DAMA/LIBRA

DAMA/LIBRA has observed with high statistical significance an annual modulation in the low energy spectrum of its NaI detectors

- Period = 1 year, phase = June 2 ± 7 days; 9.3 σ signal
- Results in tension with many WIMP searches

- Several experiments to directly probe the modulation signal with similar detectors (NaI, CsI): ANAIS, DM-Ice, KIMS, SABRE

Status & perspectives:

- Cosine 100 kg running since September 2016
- ANAIS 112 kg started operation in August 2017 and will get 3\sigma significance in 5 yr
- SABRE 5 kg proof of principle starting
- SABRE 50 kg South (Australia) scheduled to start this year (2019)
- DAMA/LIBRA III (1 ton) R&D underway

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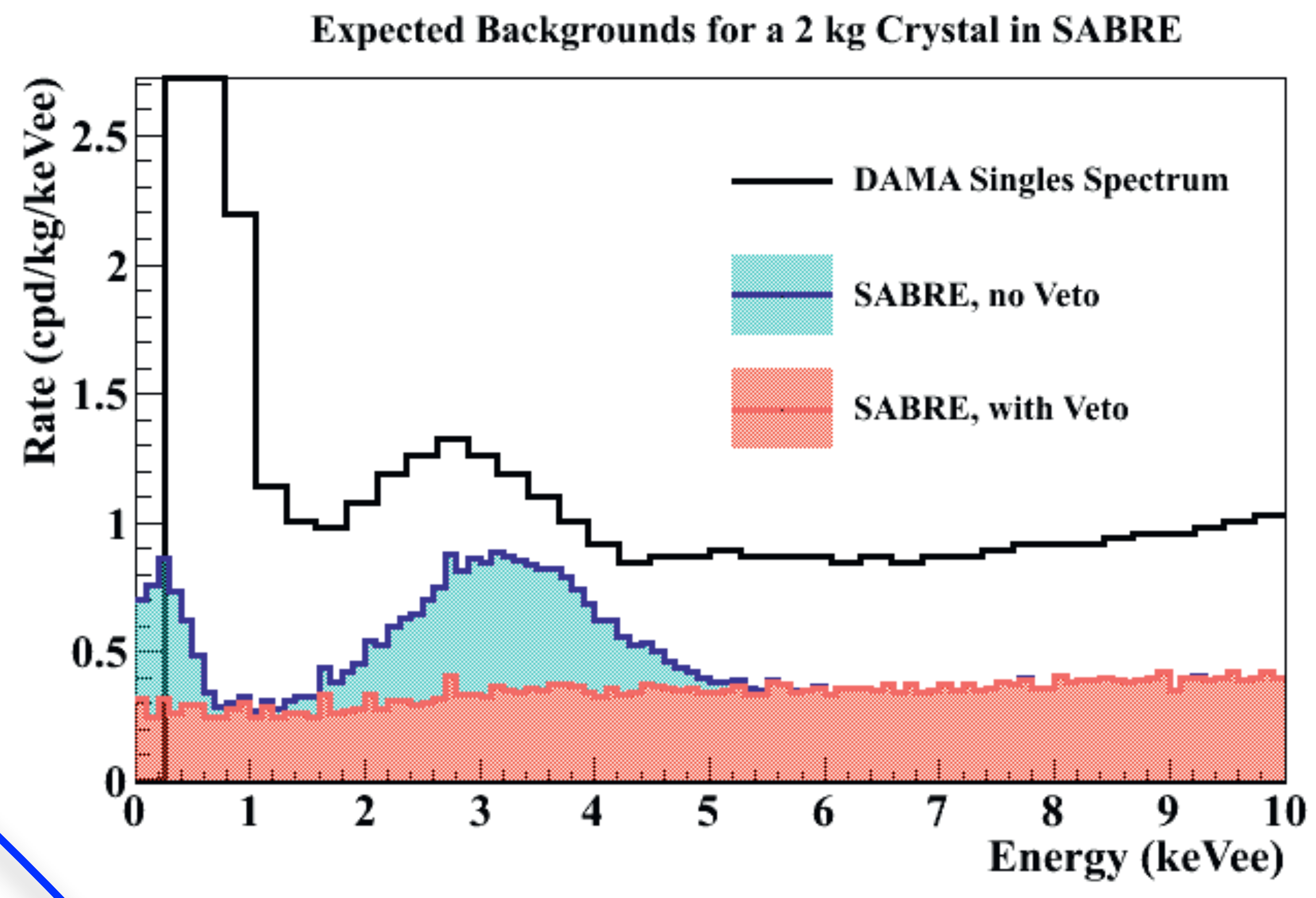

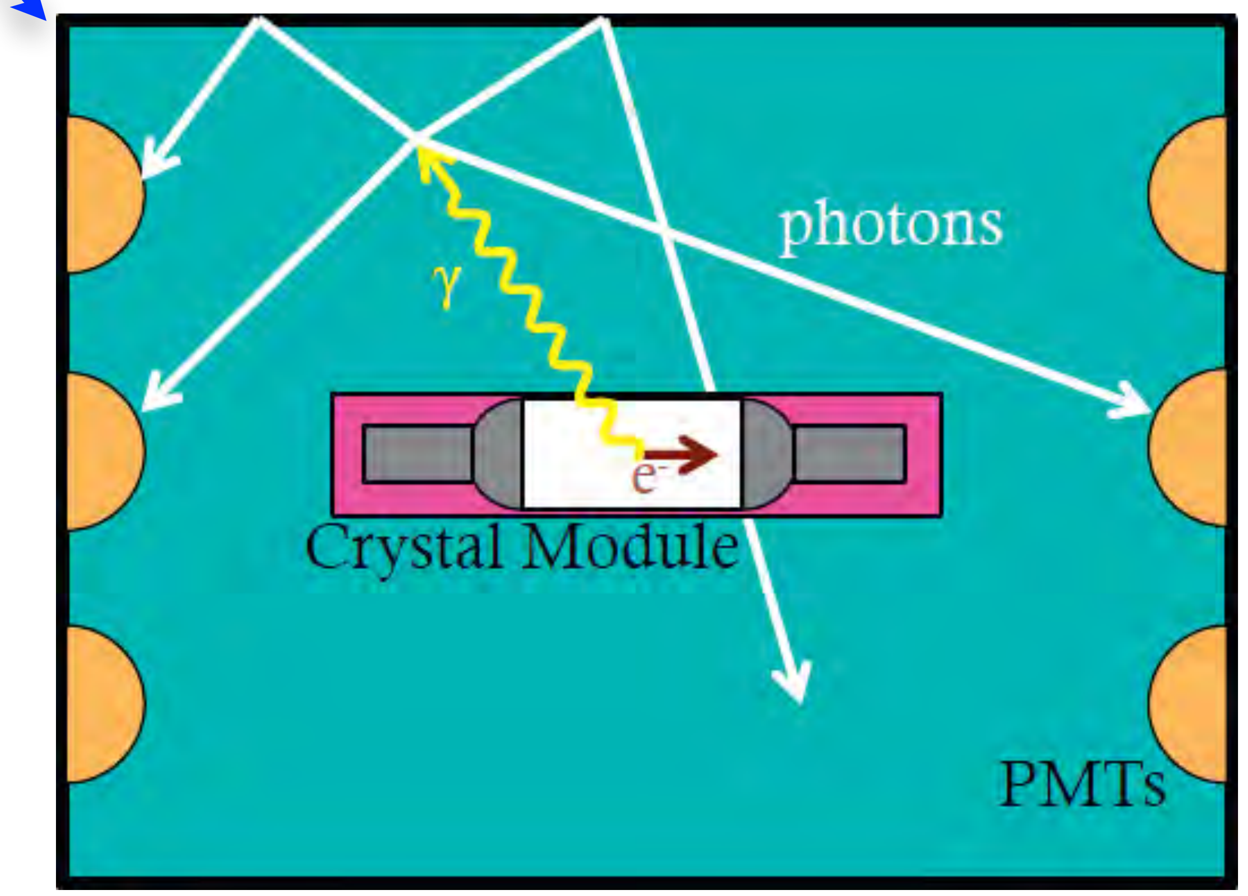

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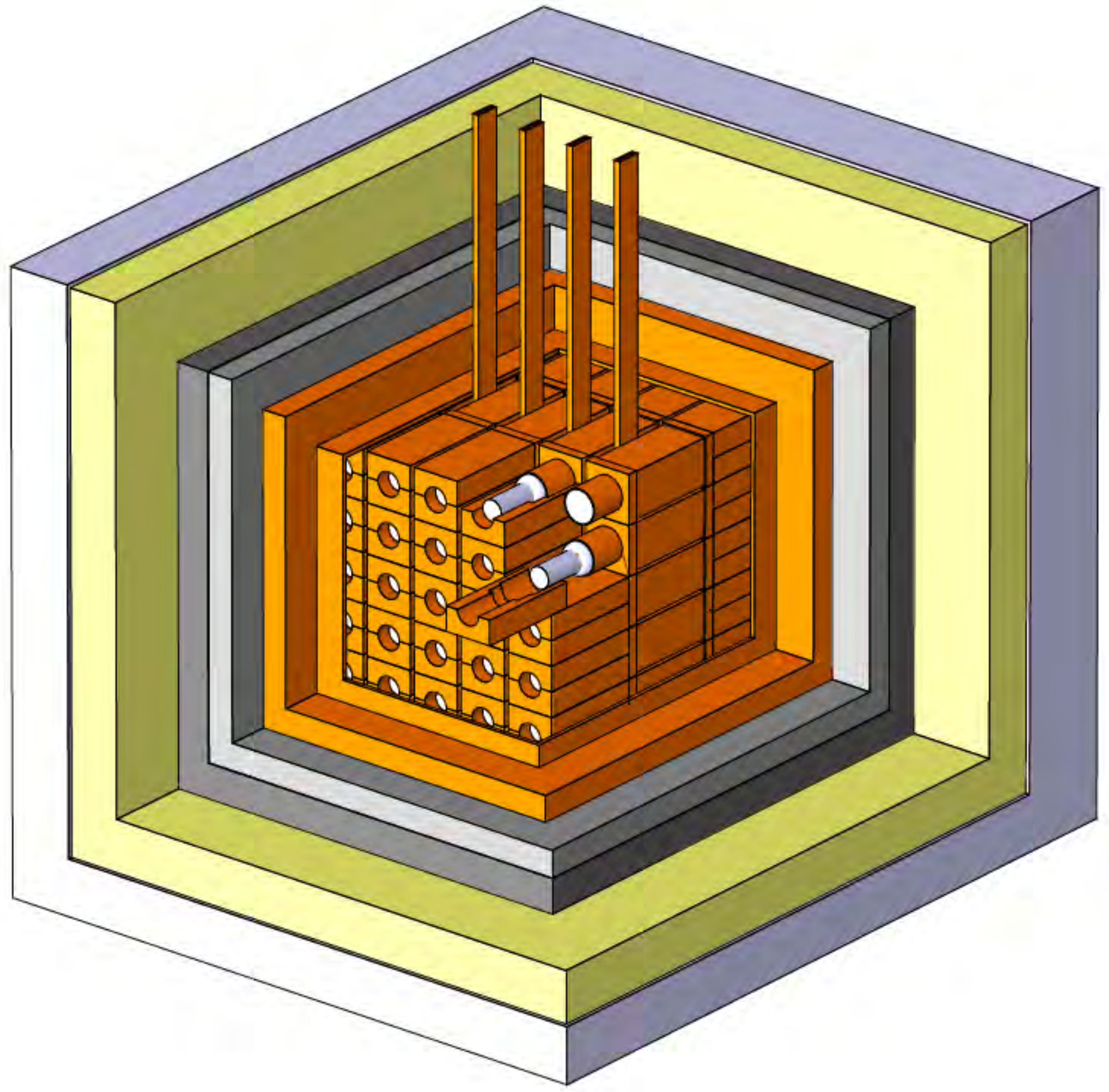
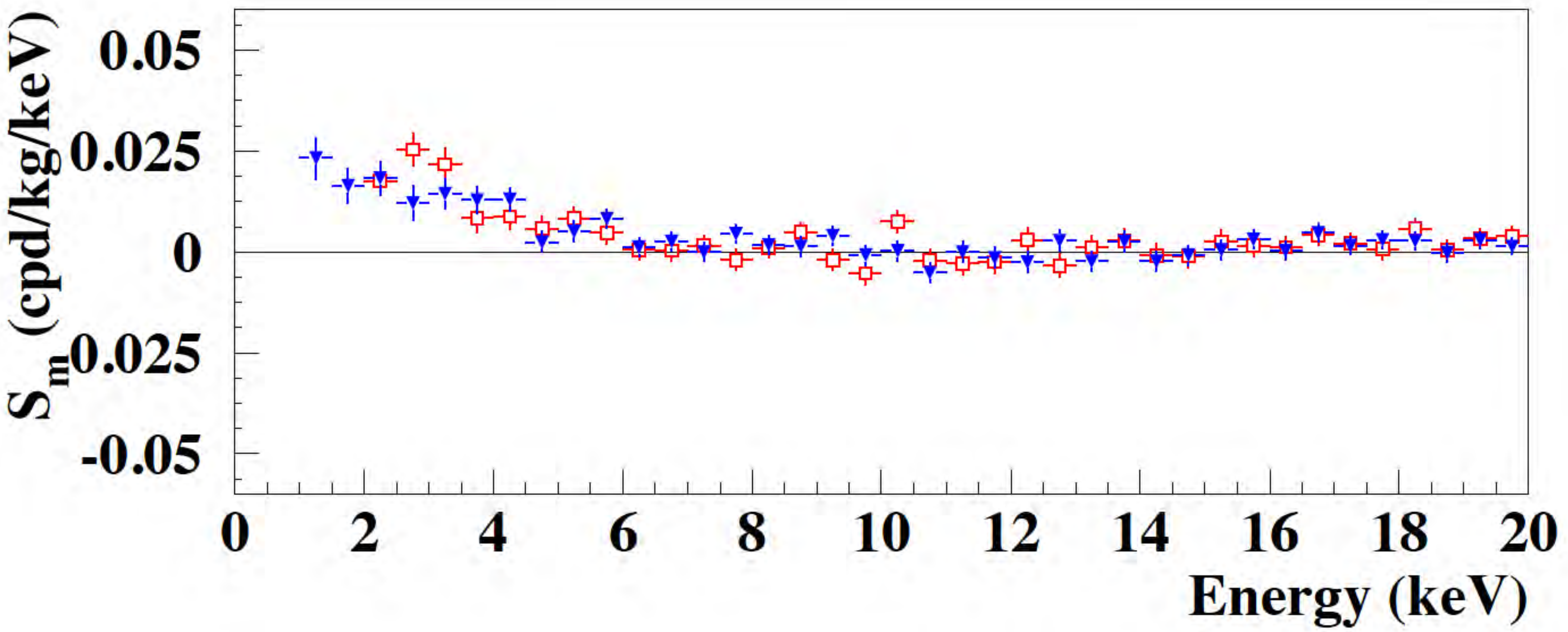
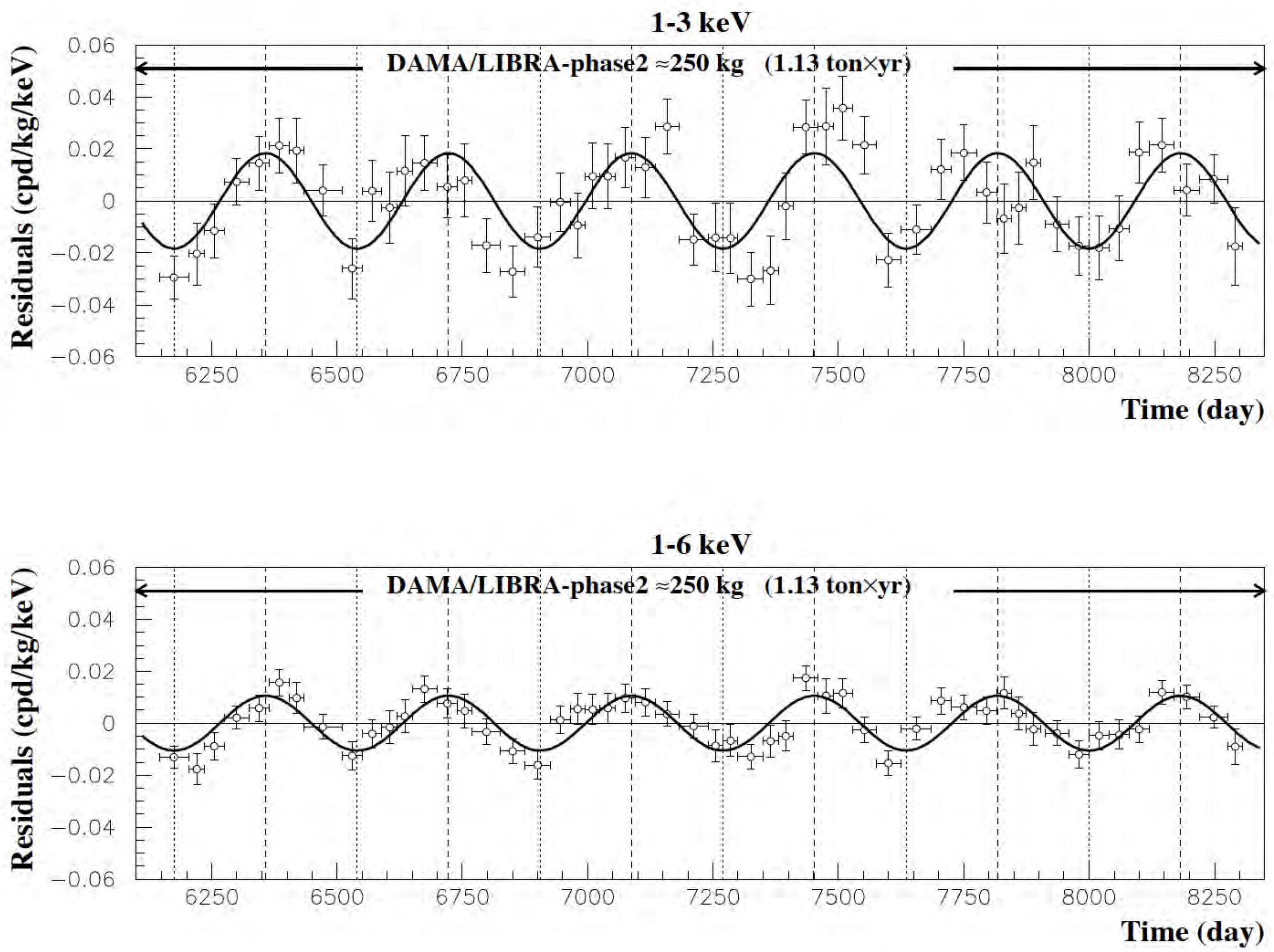
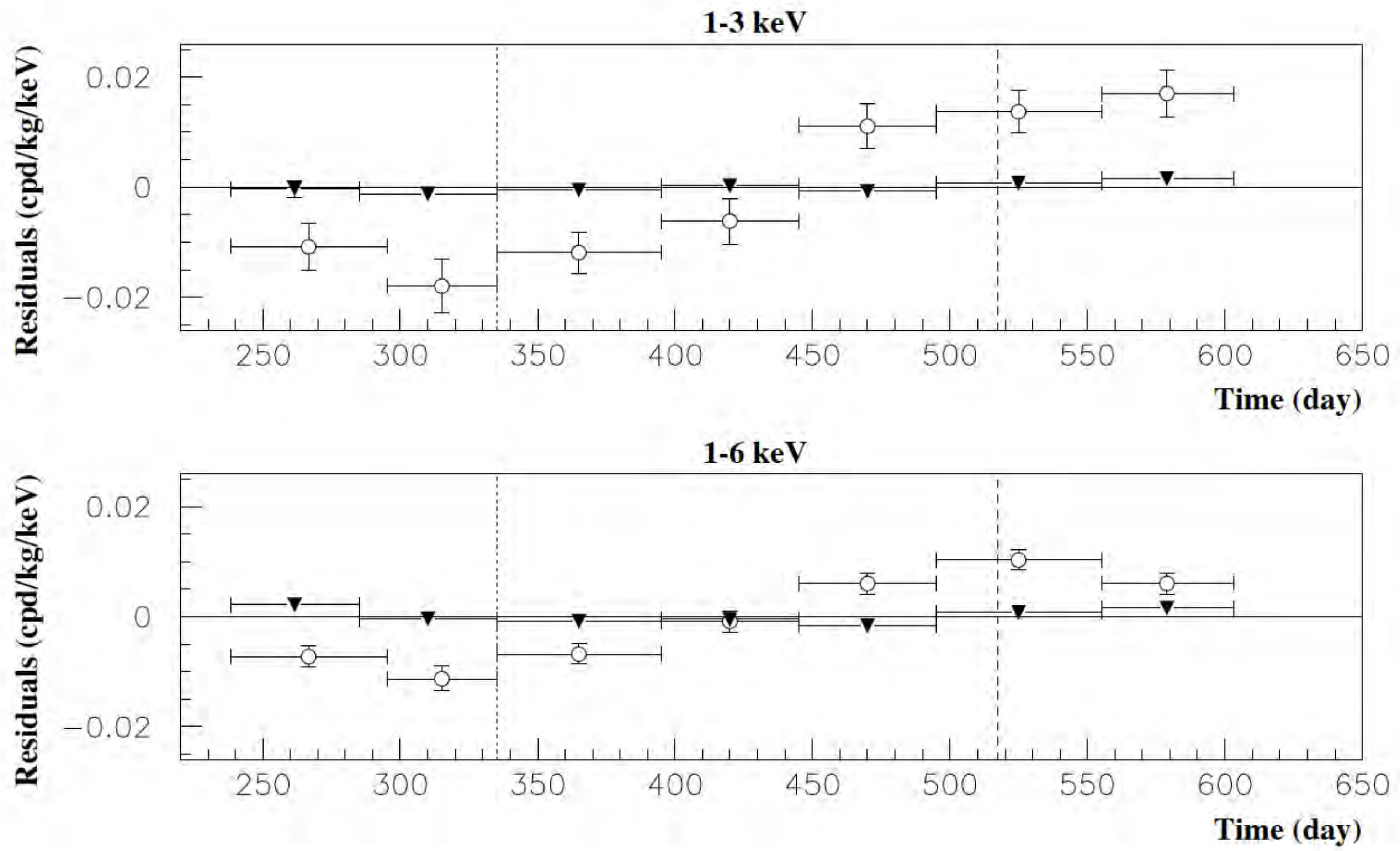
DAMA/LIBRA



- 250 kg of high-purity NaI
- Modulation signal observed with impressive statistical significance
- No correlation with possible background sources identified so far

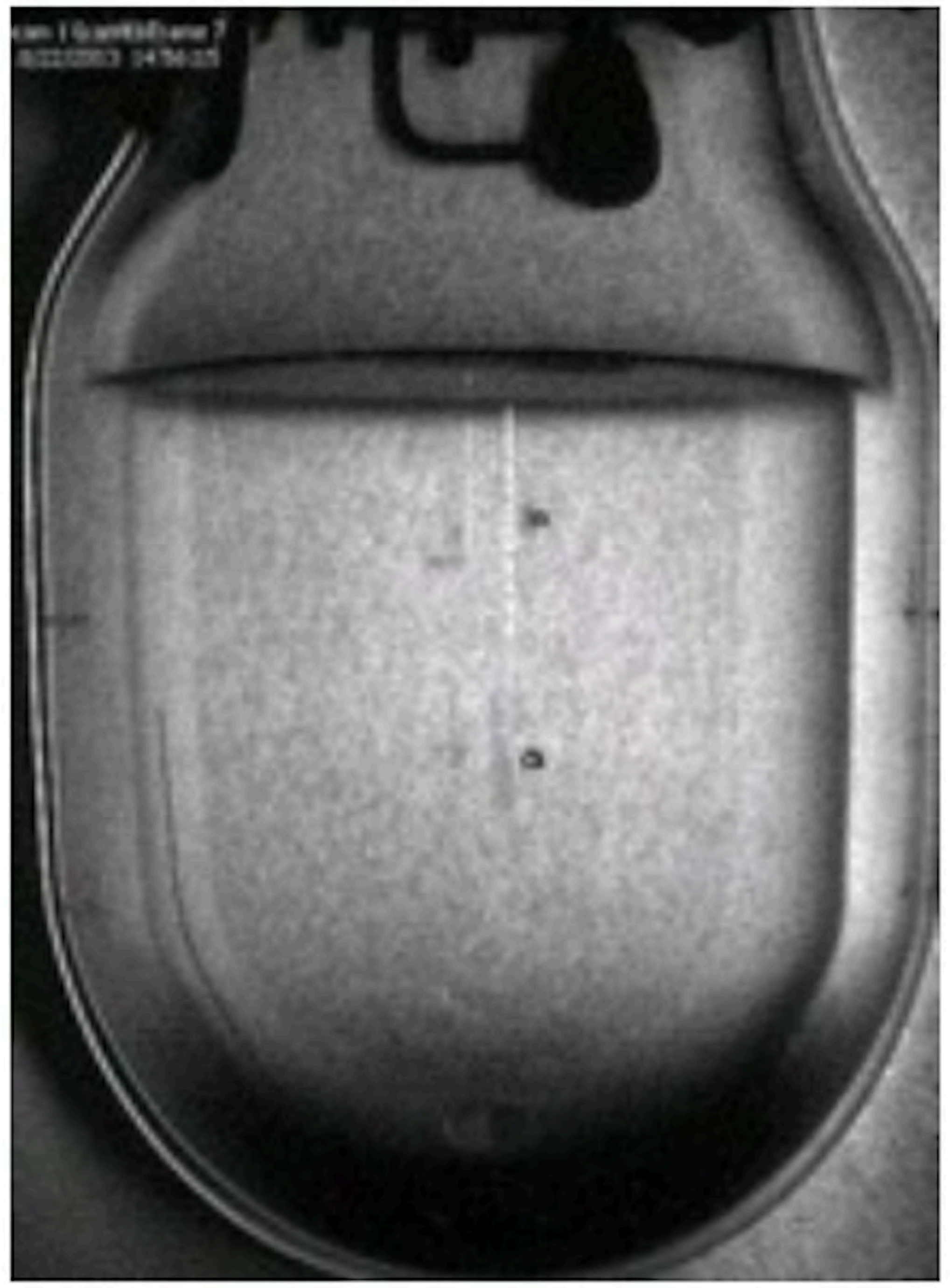






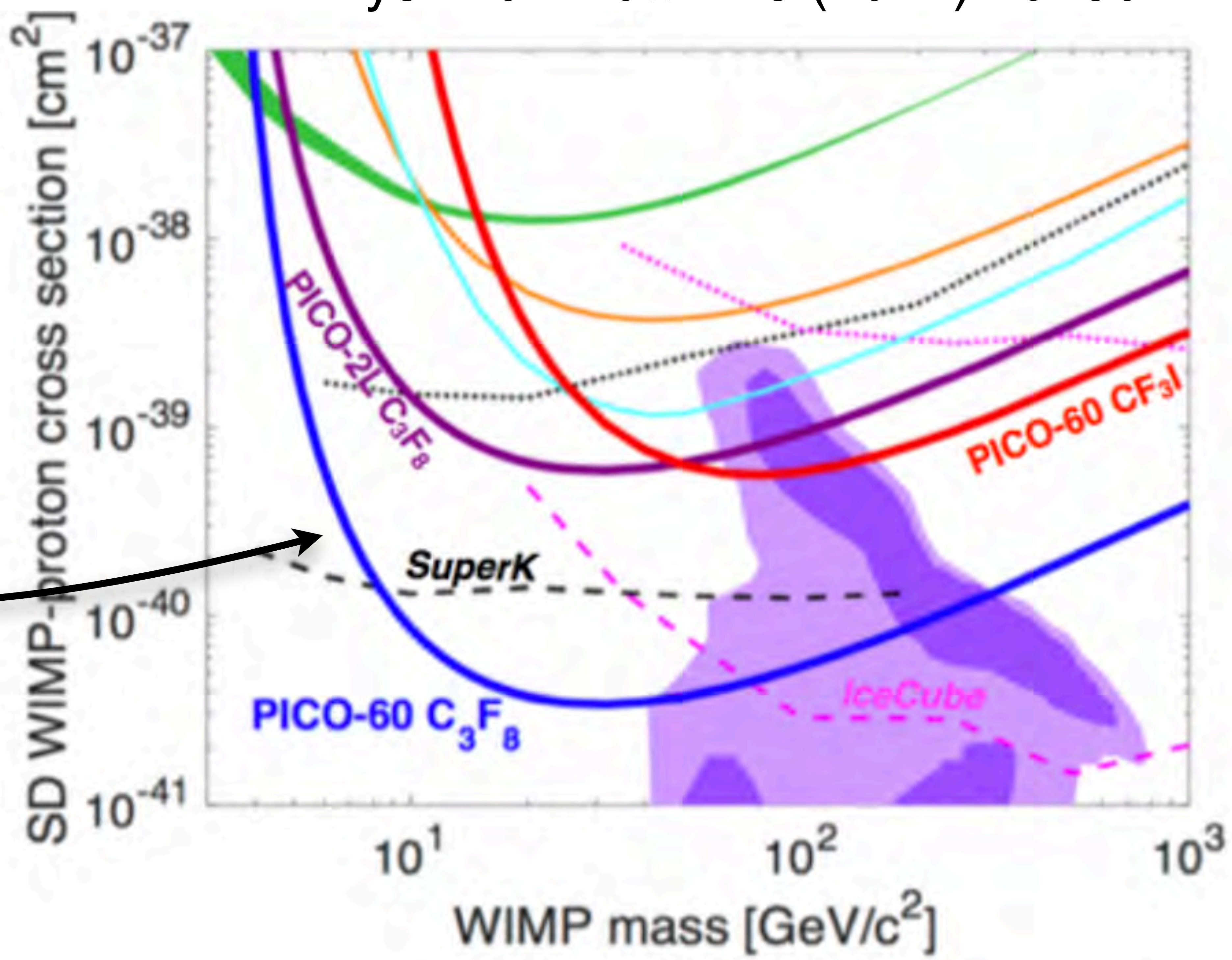
Bubble chambers

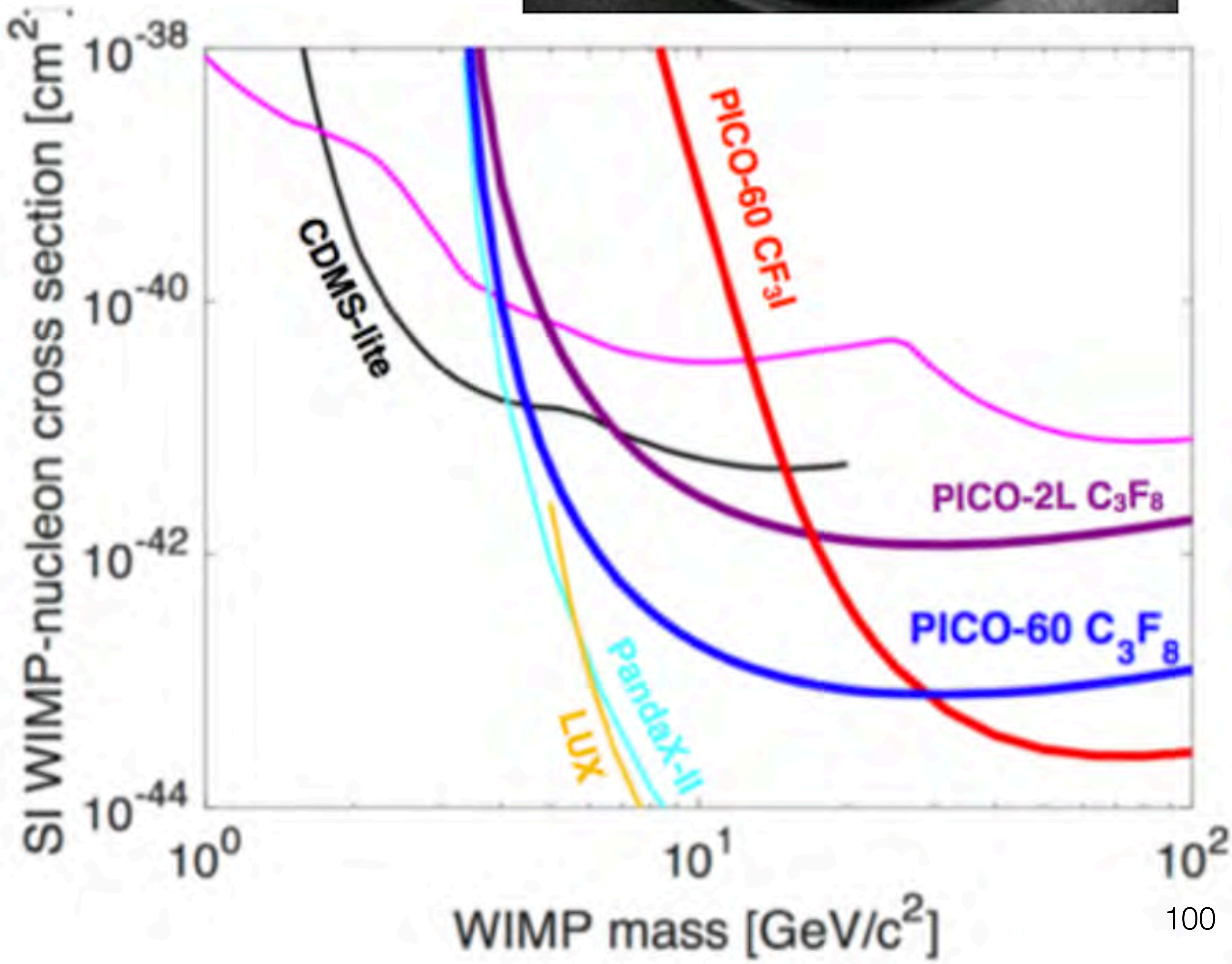
- Bubble nucleation in superheated liquids, target can include spin-independent proton targets (F)
- γ's and β's do not originat bubbles while α's can be discriminated with acoustic signals
- Best result: PICO 60 2017 run (30 d) with 52 kg and 3.3 keV theshold



best SD WIMP-proton limit:
$3.4 \cdot 10^{-41}$ cm^2 at 30 GeV/c^2

Phys. Rev. Lett. 118 (2017) 251301

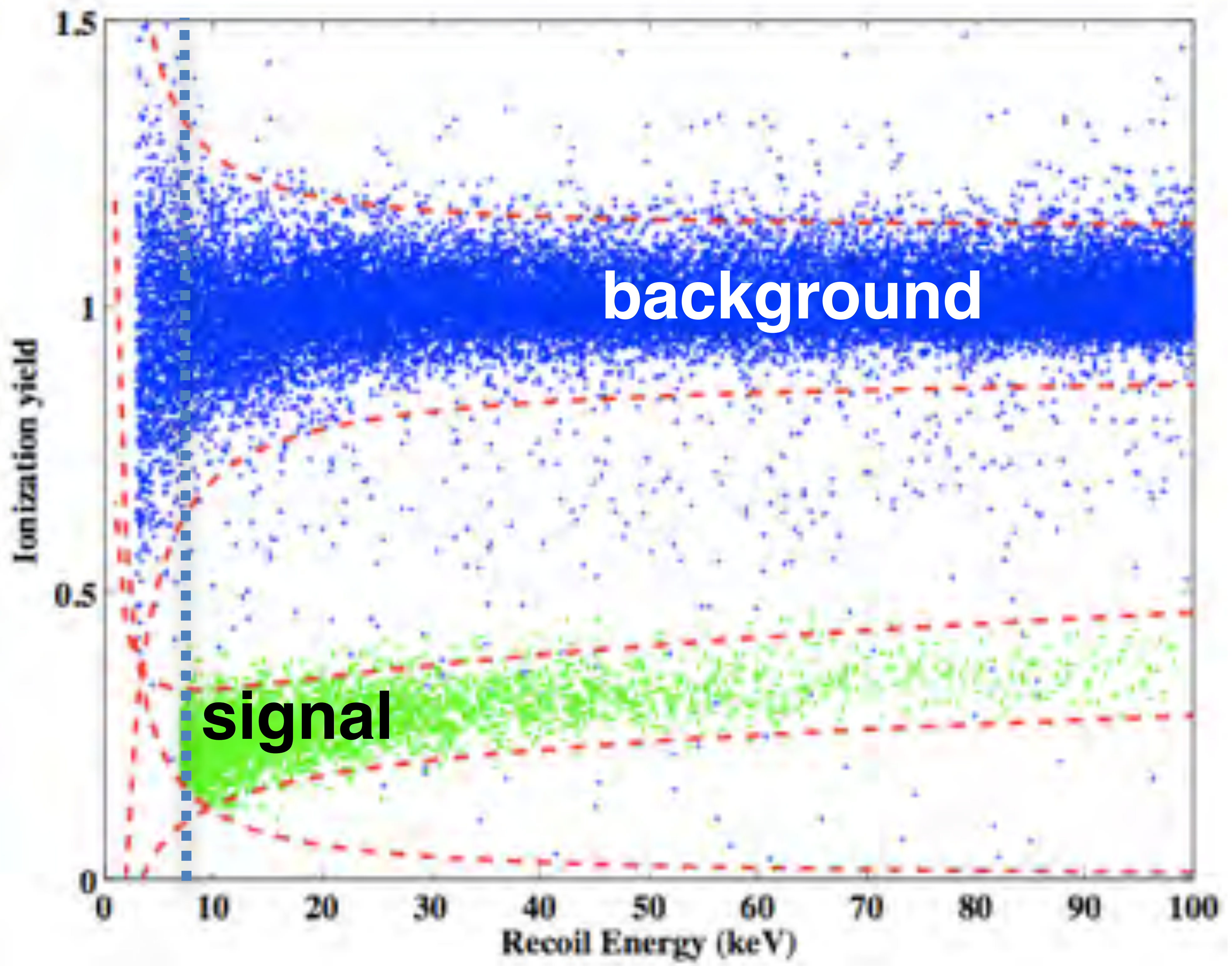


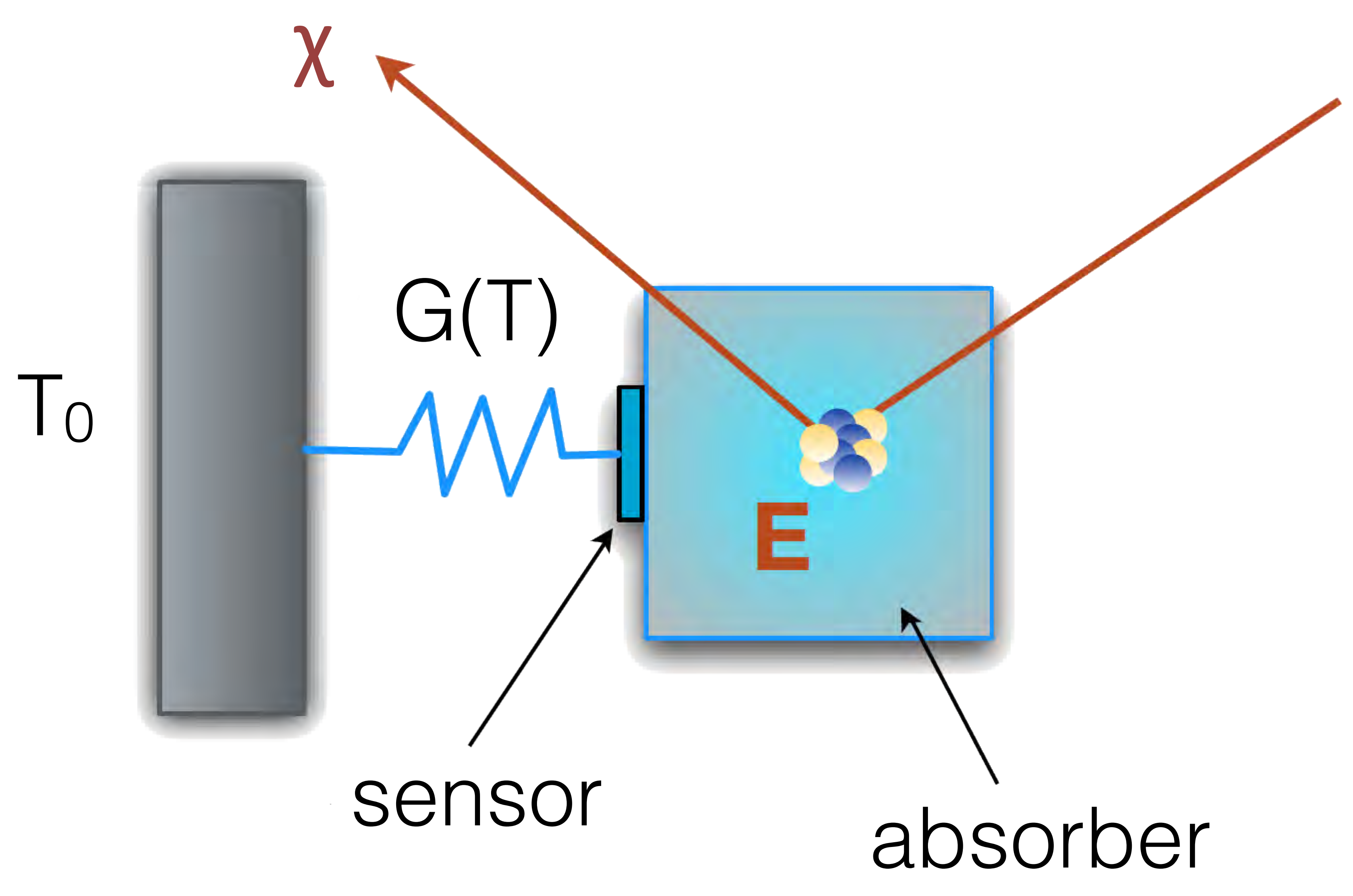


Low temperature detectors (LTD)

- Detect a temperature increase after a particle deposits energy in an absorber
- Absorber masses from ~100 g to 1.4 kg; TES/NTD read out small T changes

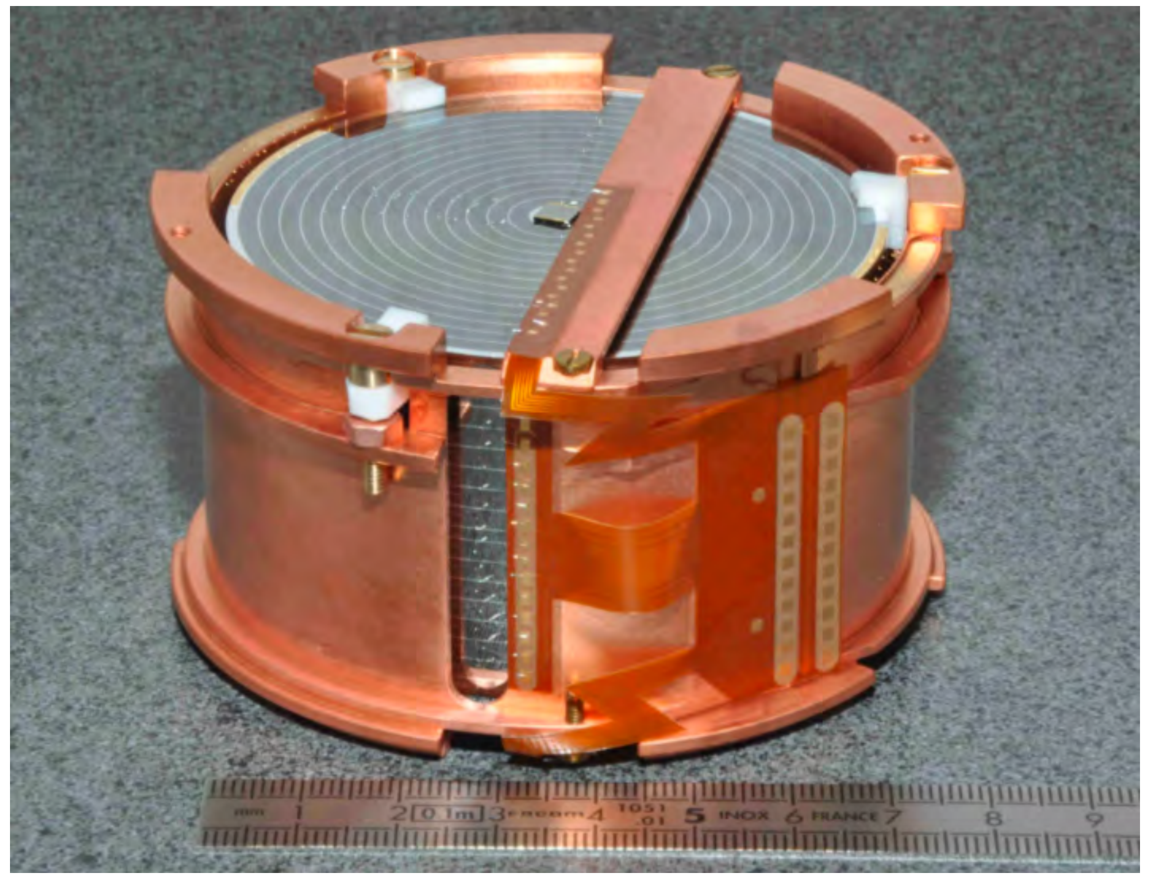
$$\Delta T = \frac{E}{C(T)} e^{-t/\tau} \qquad \tau = \frac{C(T)}{G(T)}$$



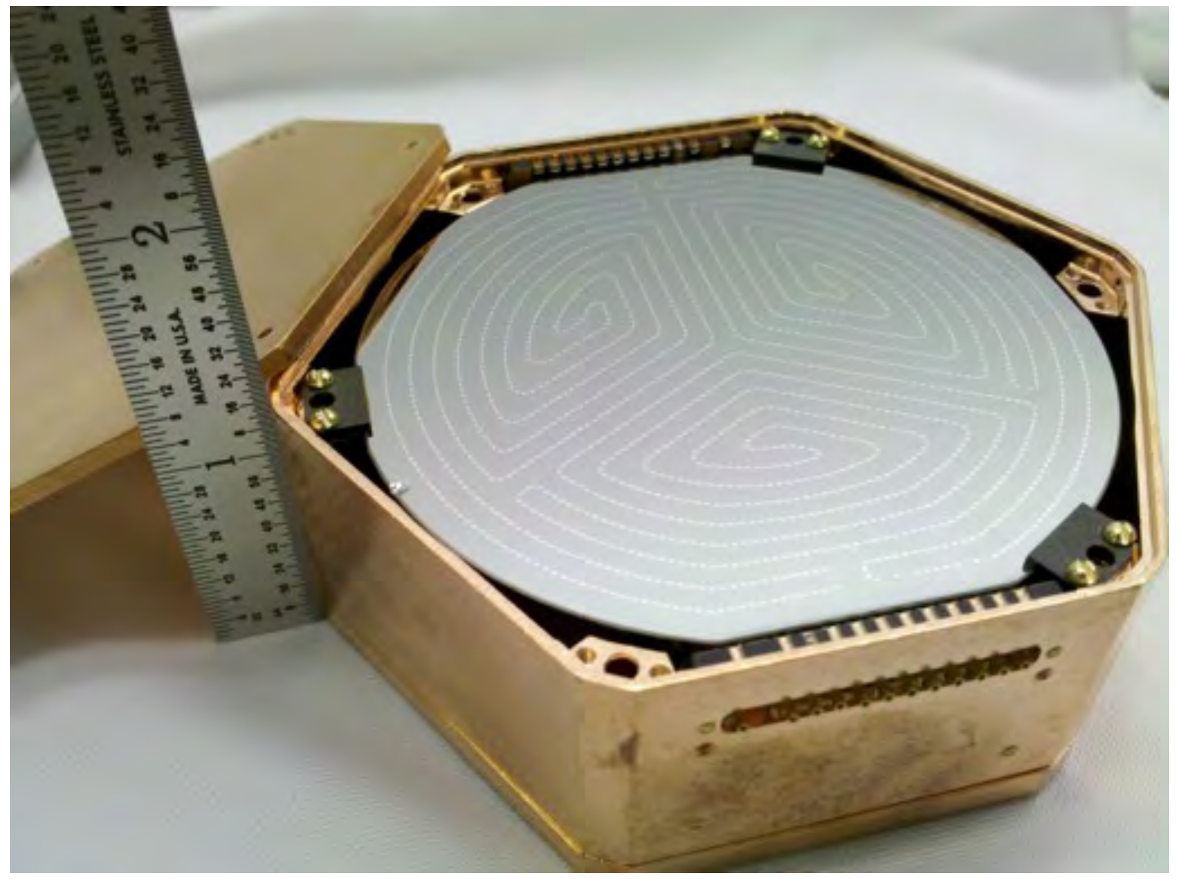


CRESST (CaWO4

EDELWEISS-III (Ge)



SuperCDMS: Ge, Si



Cryogenic bolometers

SuperCDMS/EDELWEISS 2 techniques

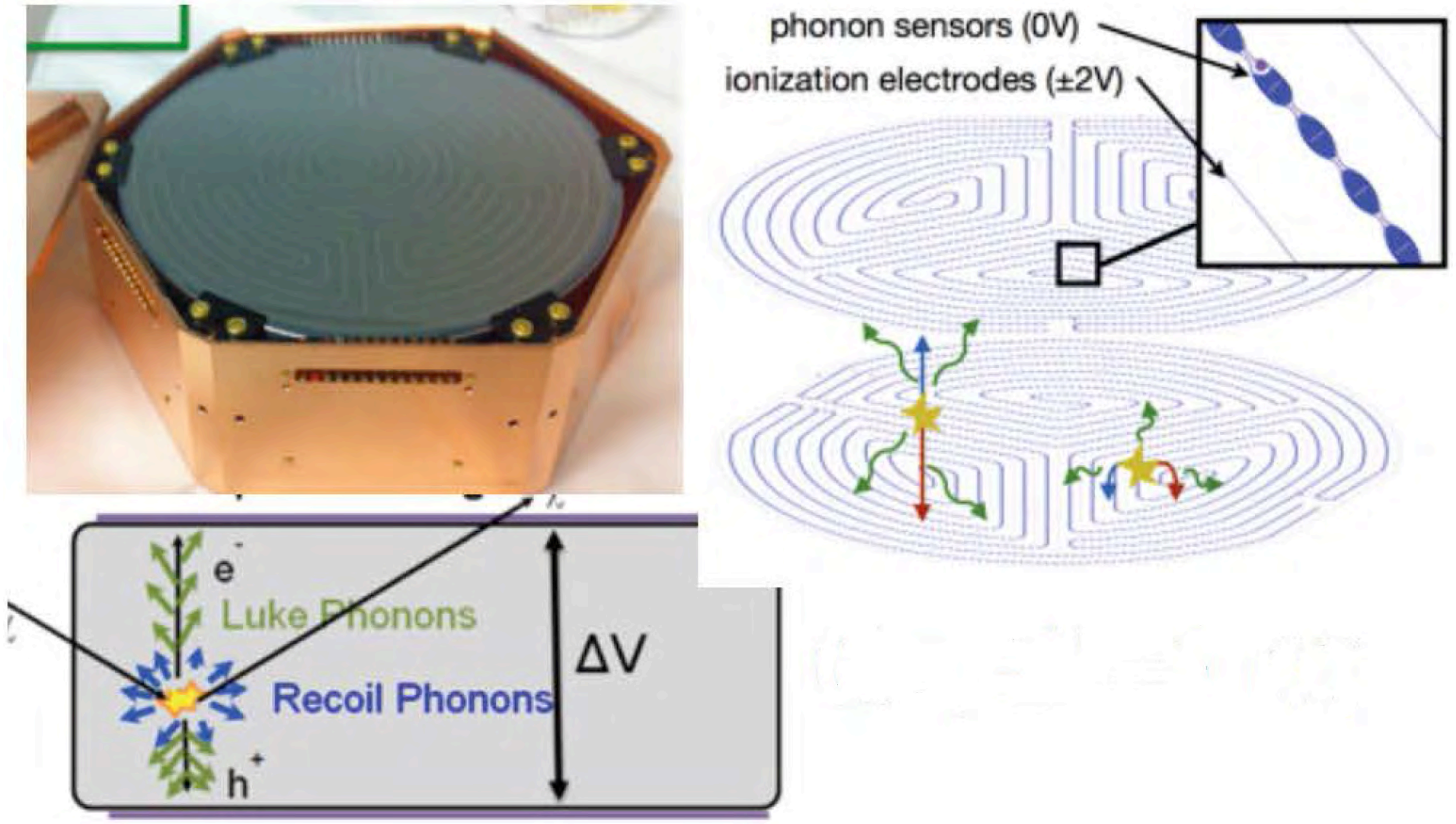
- HV (CDMSlite) - Luke phonons: low threshold, no discrimination
- iZIP/FID - ionization and phonon signals with interleaved sensors discriminate against electronic recoils and surface events

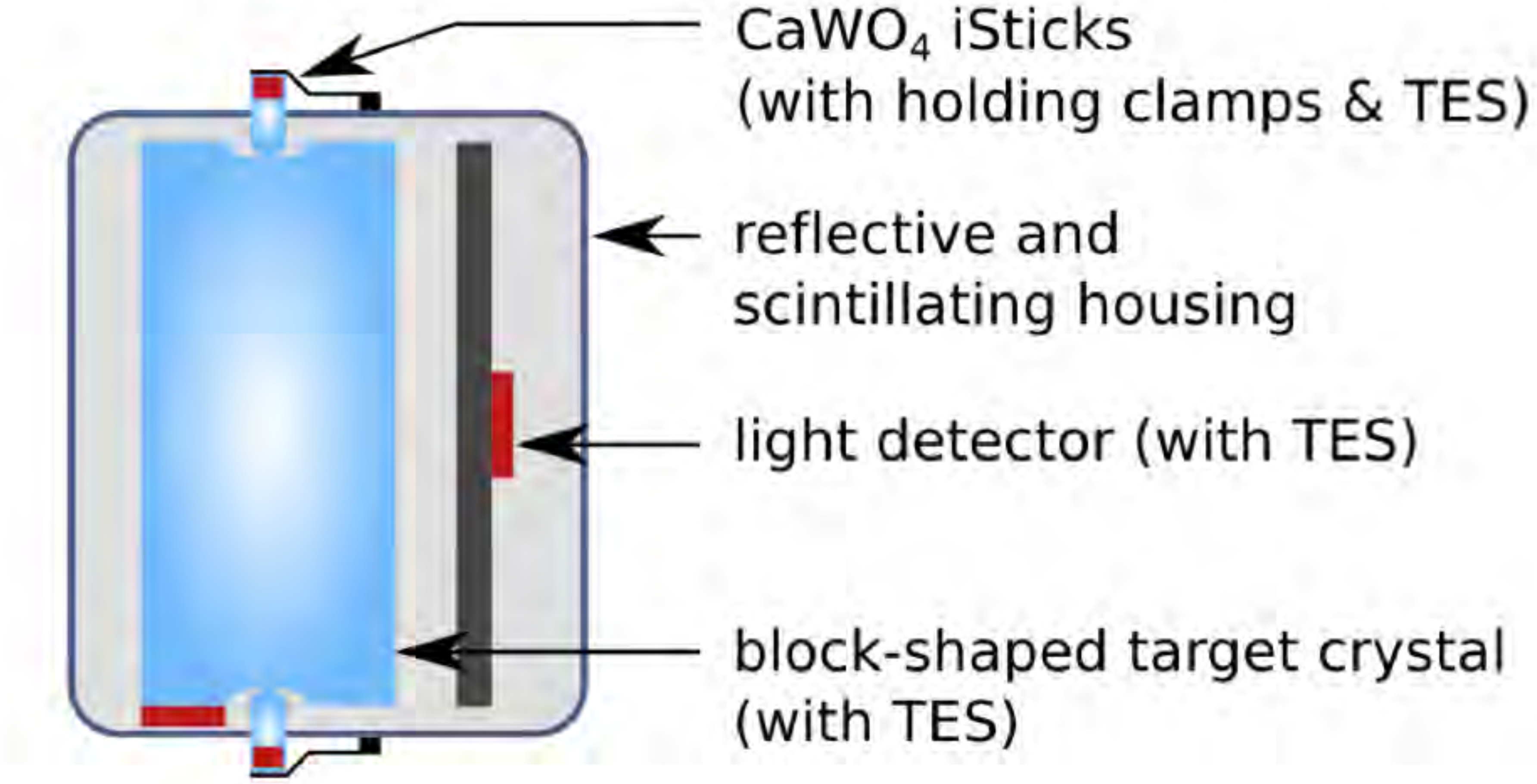
CRESST

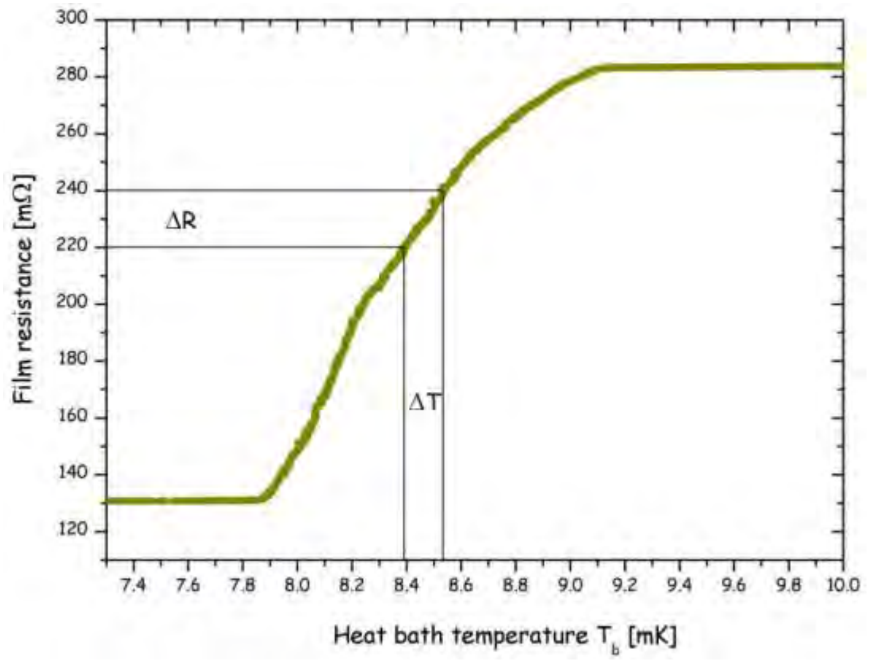
- CaWO4 crystals for phonons and scintillation

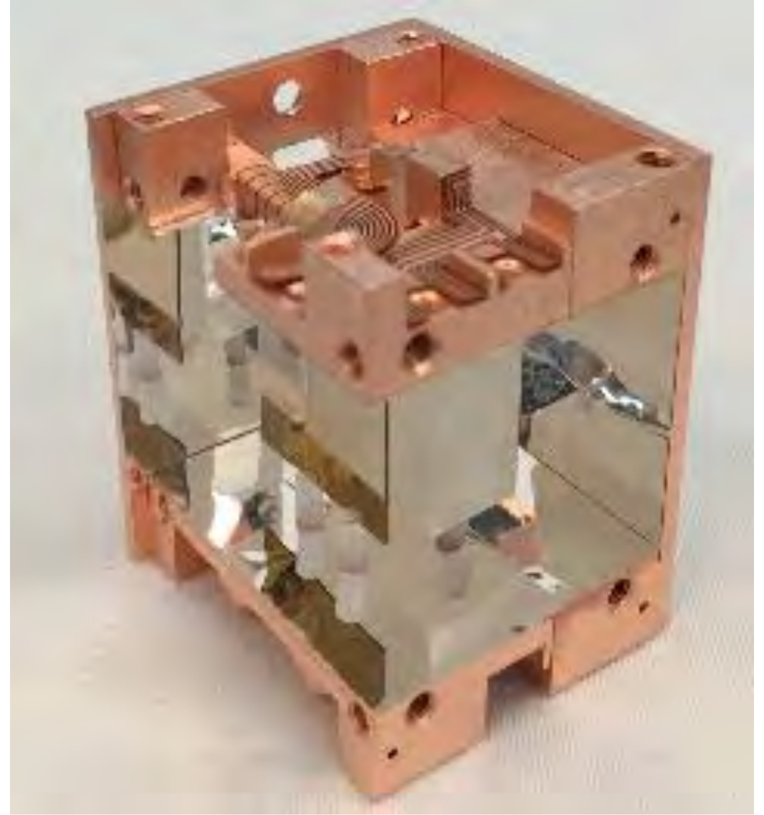
DAMIC

- Si CCD





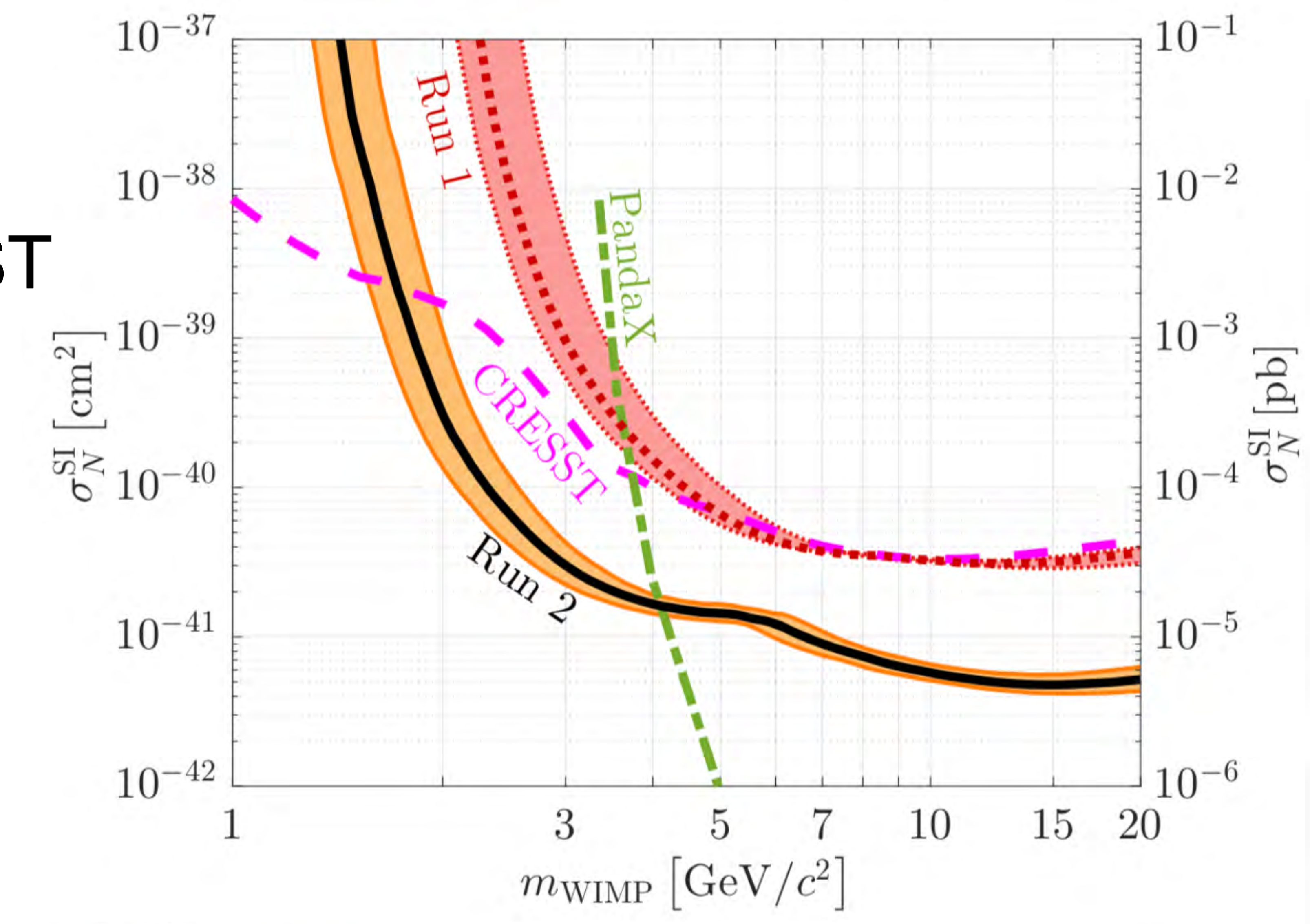




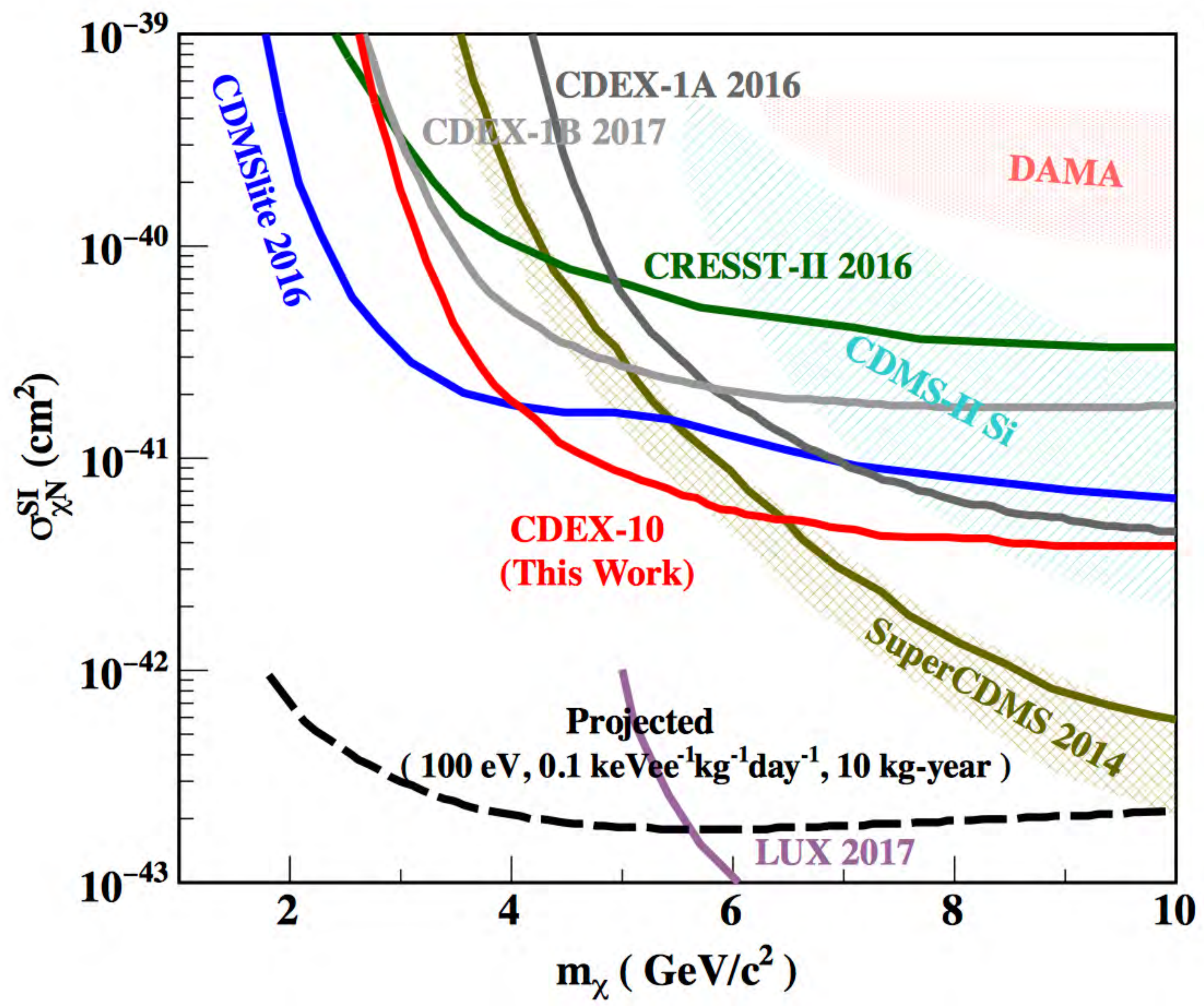
Low temperature detectors

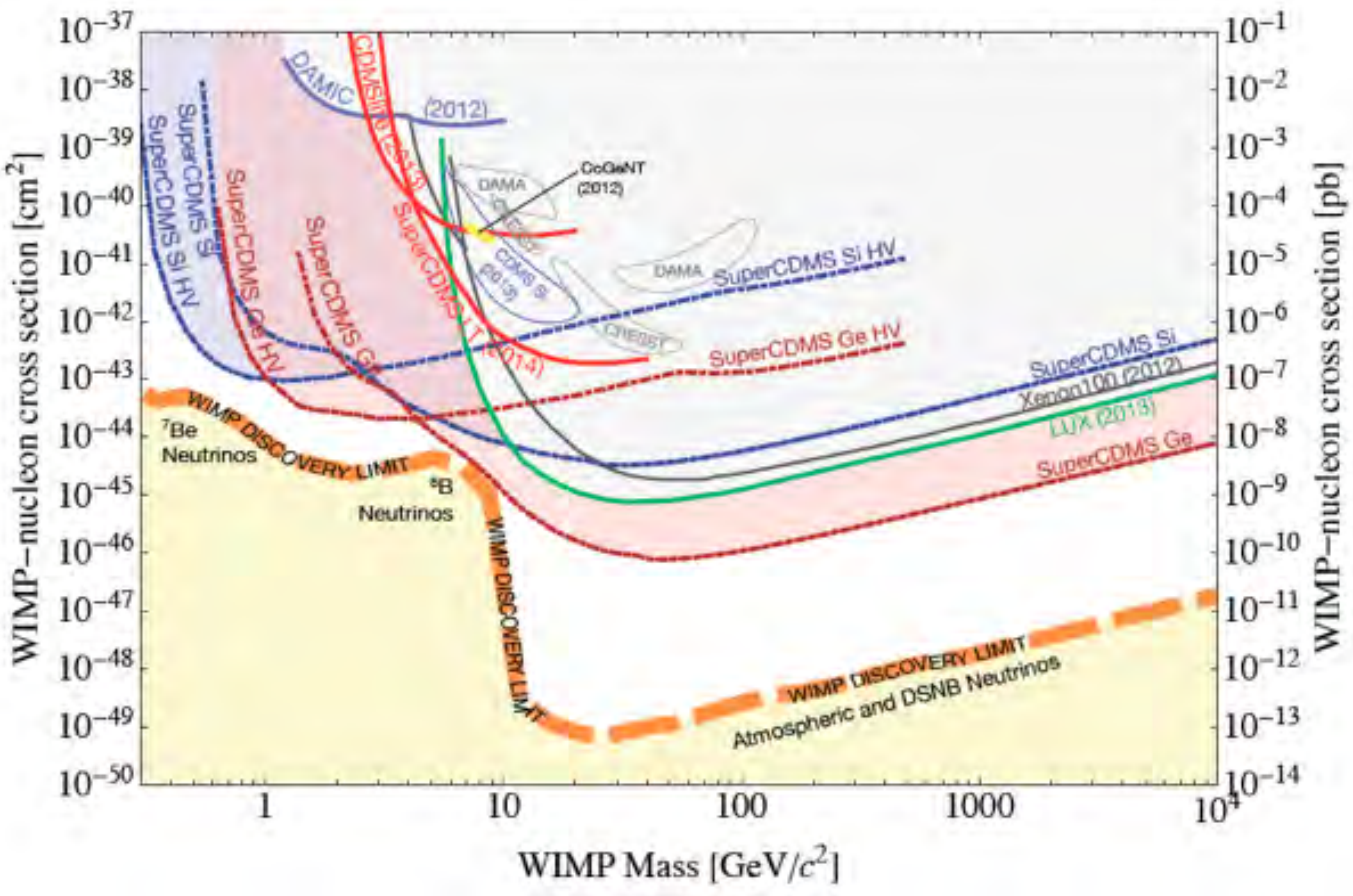
- Probe the low mass region of the WIMP's

CRESST



CDEX



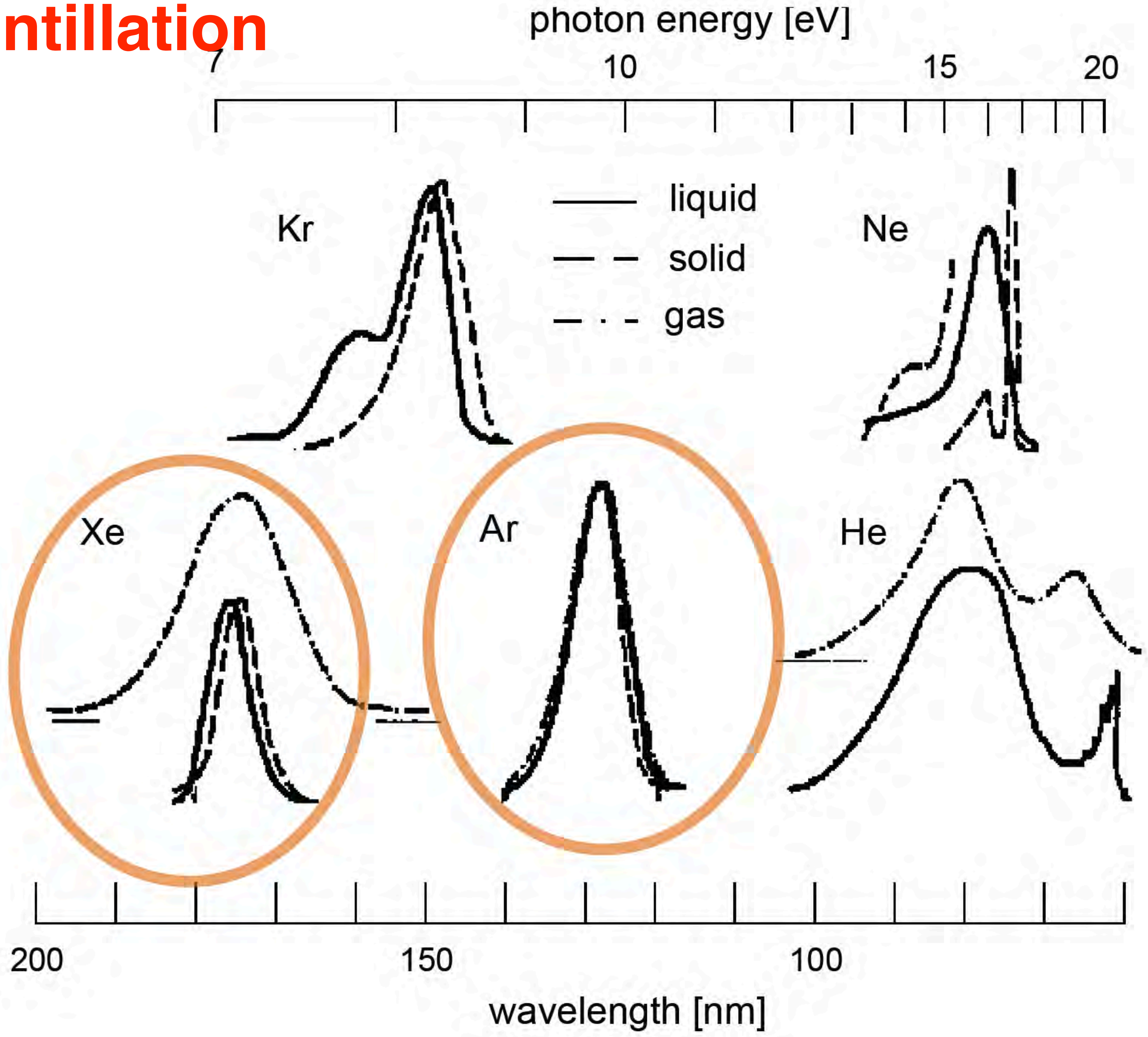


Noble liquids

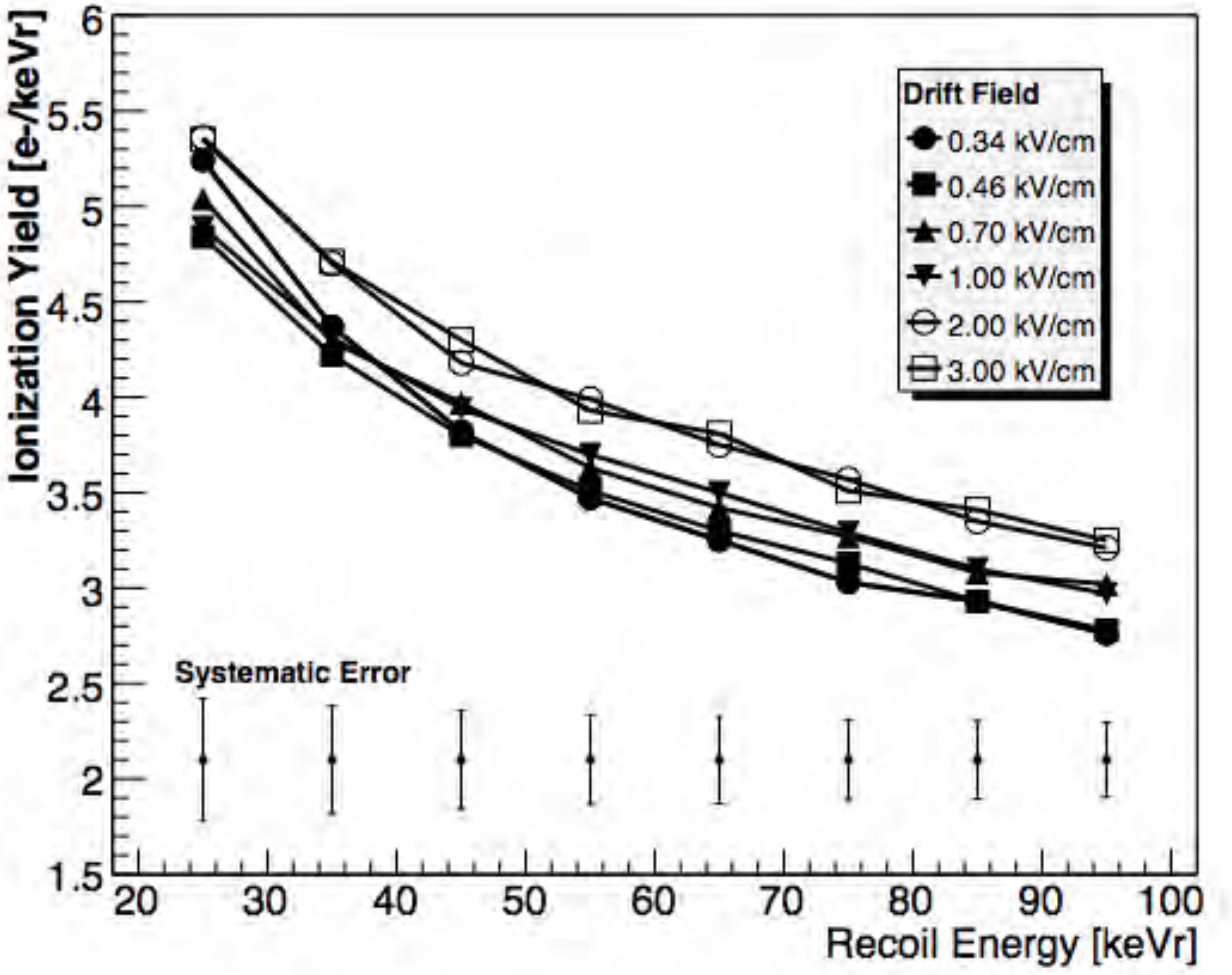
- Large masses and homegeneous targets (LNe, LAr & LXe)
- Two detector concepts: single & double phase
- 30 position reconstruction ---+ fiducialization
- Transparent to their own scintillation light

- High light and charge yield
- Xenon and argon are very common in dark matter detectors

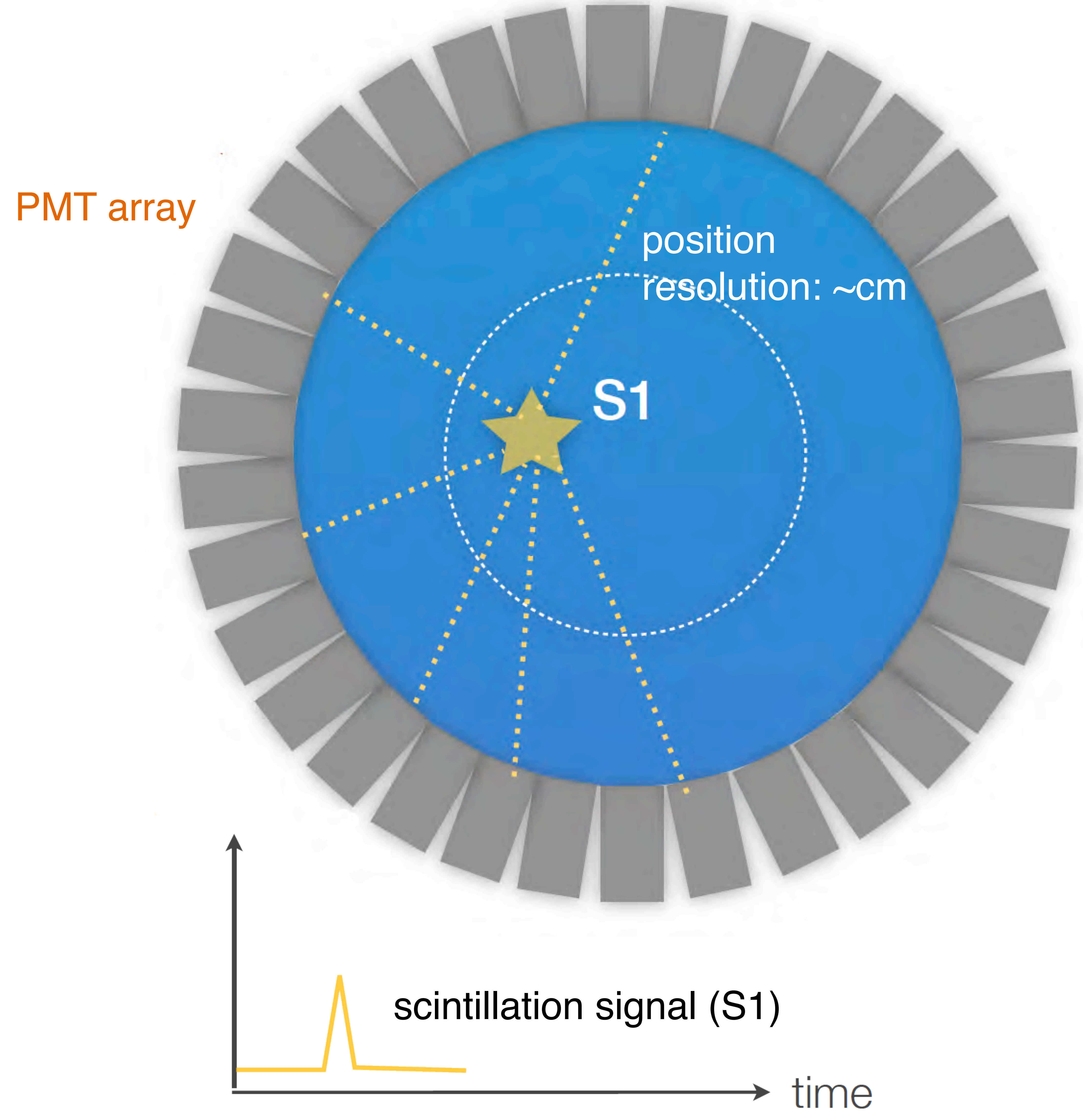
scintillation



ionisation



Single-phase noble liquid detectors

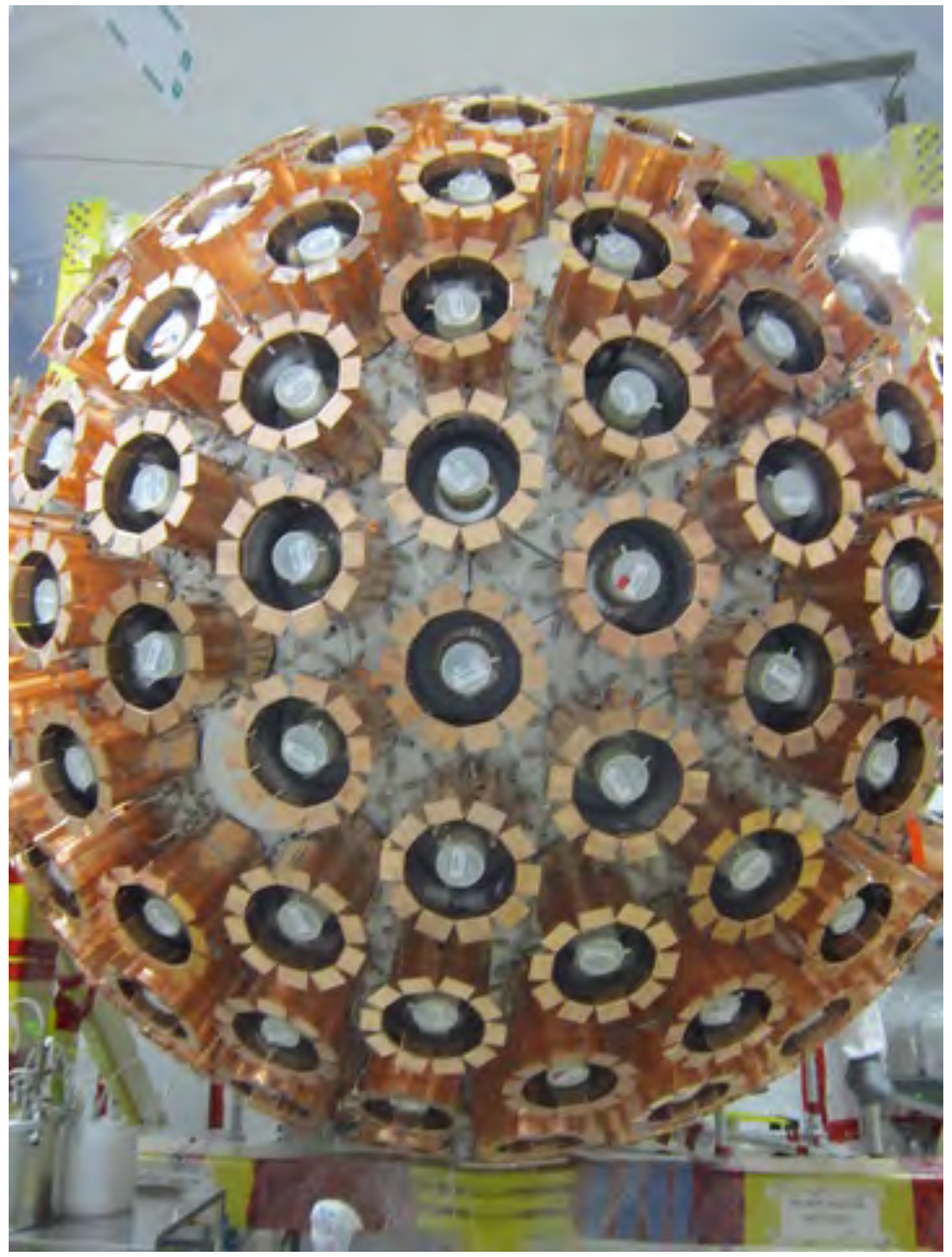


- High light yield using 4π photosensor coverage
- Position resolution in the cm range
- Pulse shape discrimination (PSD) from scintillation (LAr)

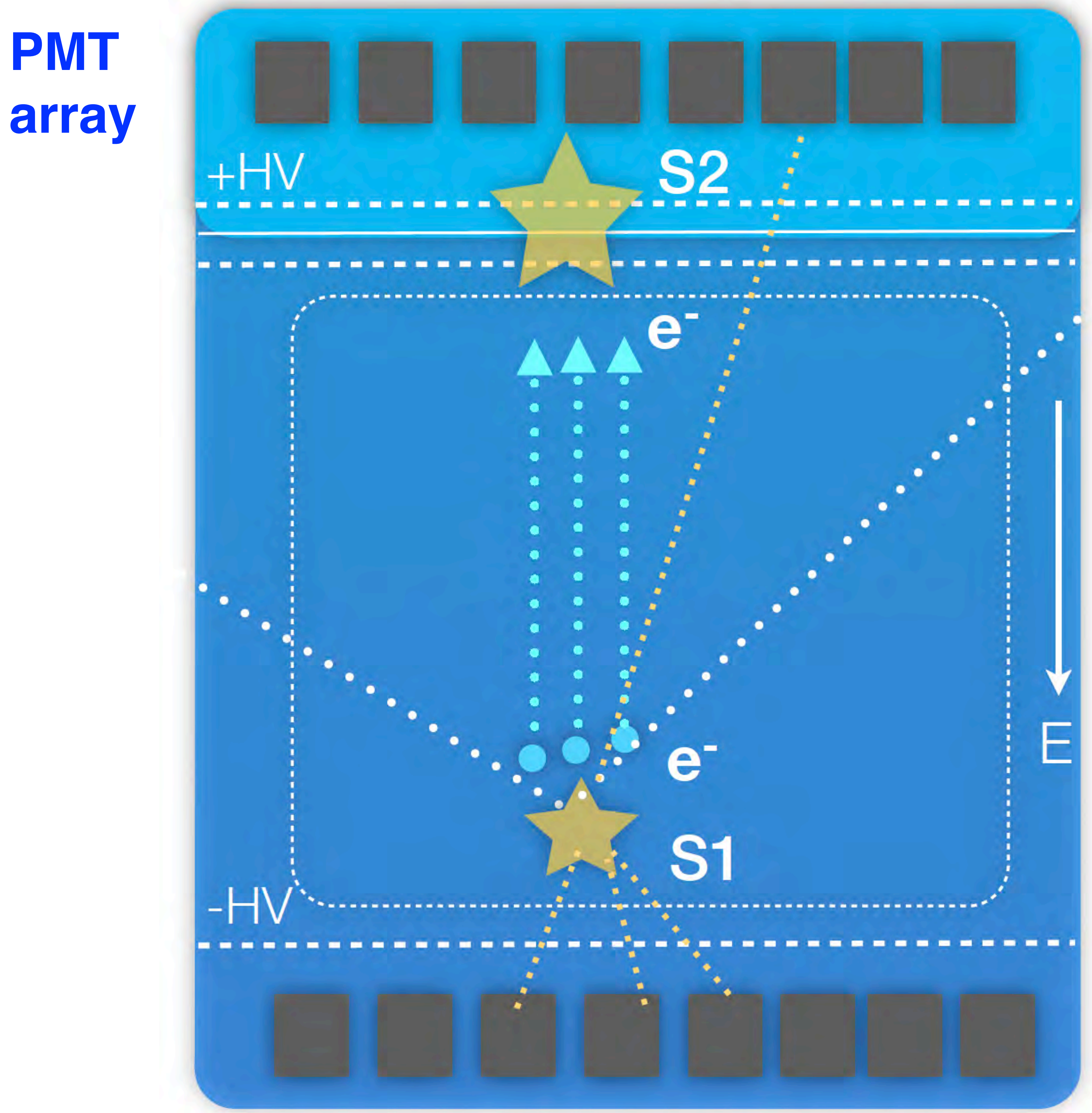
  - Instrumented LAr or LXe volume
  - Scintillation light in VUV region

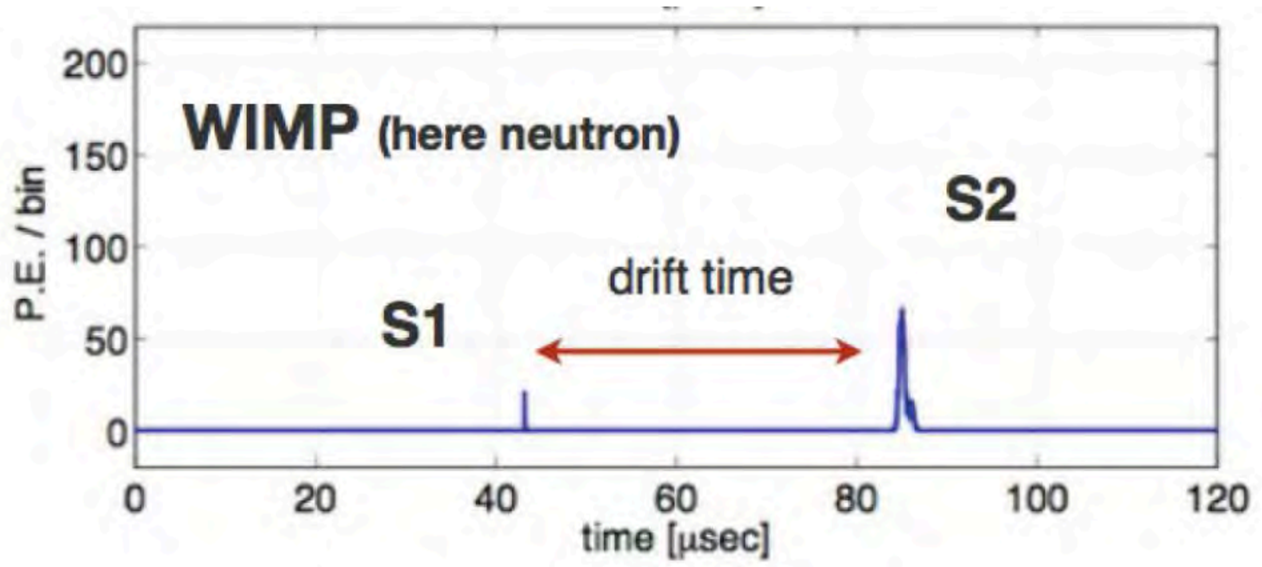
XMASS (LXe)
at Kamioka, 832 kg

DEAP-3600 (LAr)
at SNOLAB, 3.6 t



Dual-phase noble liquid detector





scintillation (S1)

ionization (S2)

- Scintillation signal (S1)
- Charges drift to the liquid-gas surface
- Proportional signal (S2)

➡ Electron/nuclear recoil discrimination

LXe: XENON100 **LXe: LUX** **LAr: DarkSide**

Xenon

- XENON100 at LNGS, LUX at SURF, PandaX at CJPL

Argon

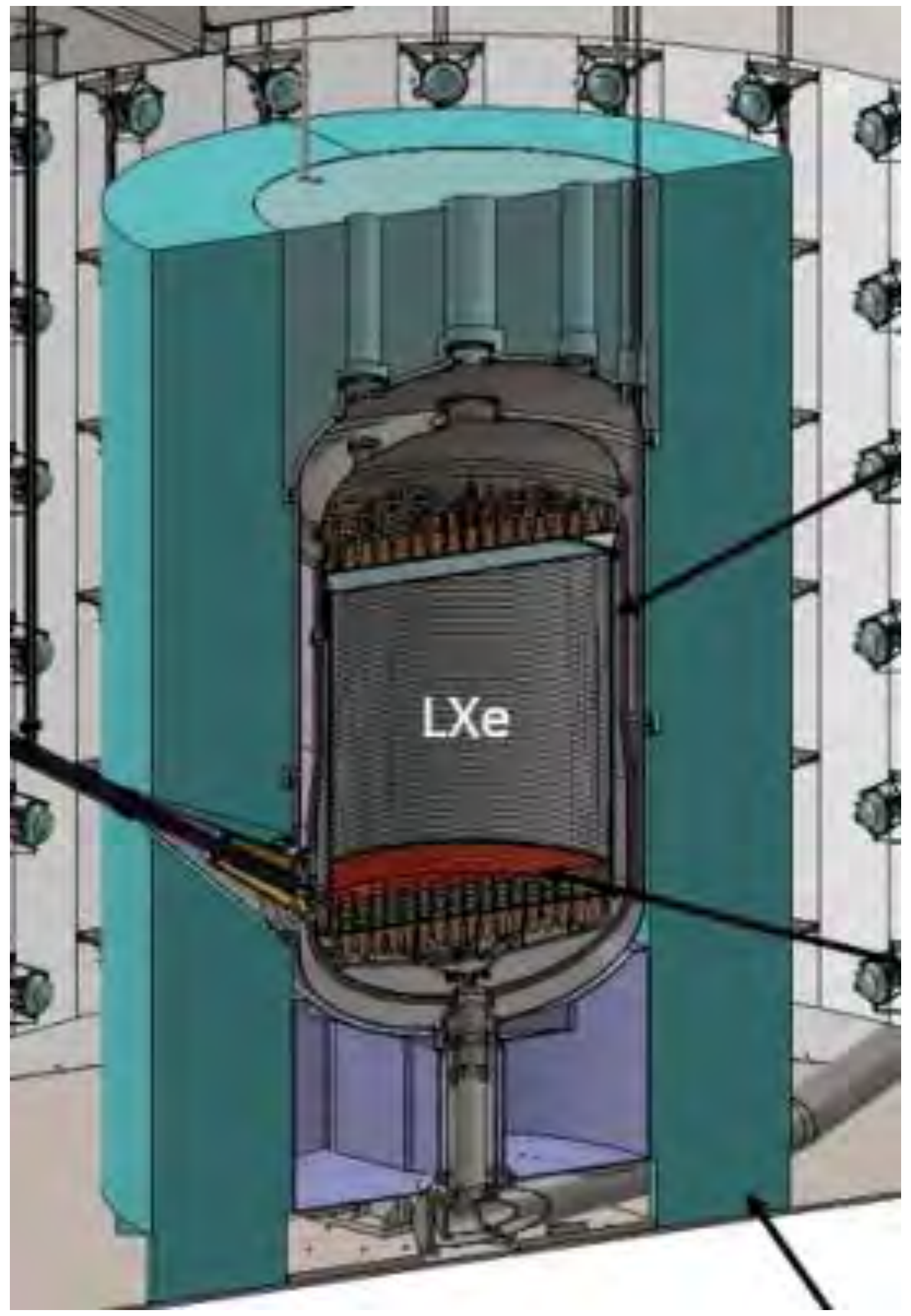
- DarkSide-50 at LNGS, ArDM at Canfranc
- Target masses between ~ 50 kg - 1 ton

Future noble liquid detectors

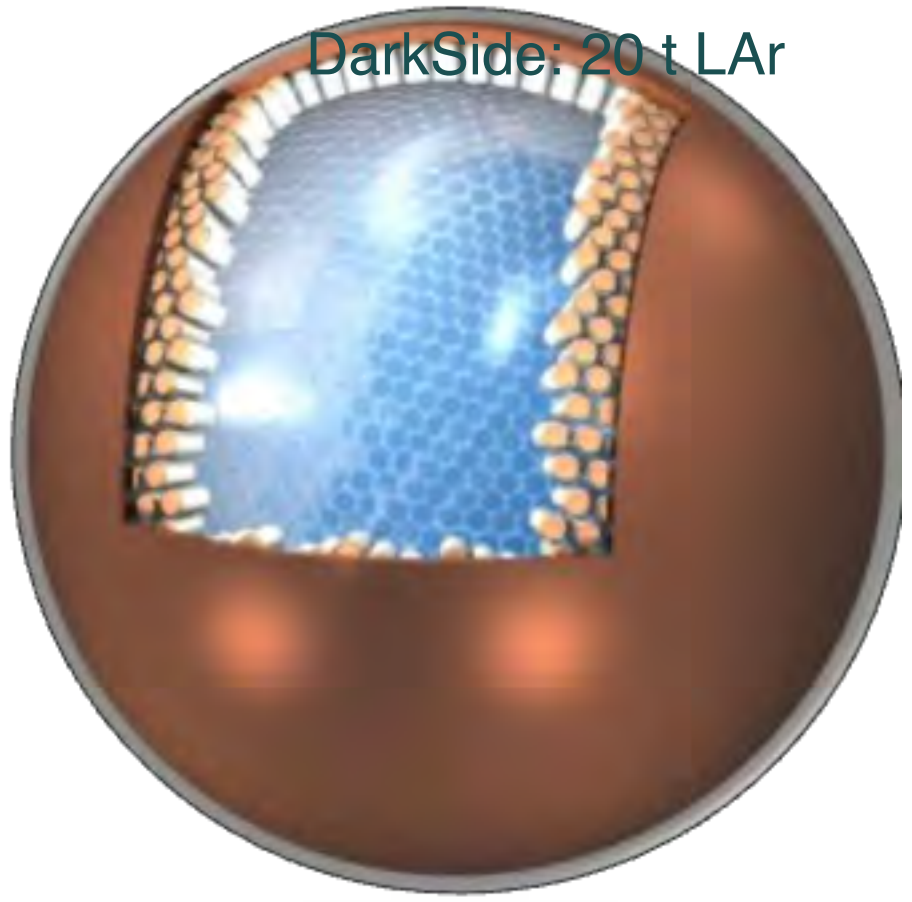
Sensitive and scalable:

- Under construction: XENON1T/nT (3.3 t/ 7t LXe) at LNGS
- Proposed LXe: LUX-ZEPLIN 7t (approved), XMASS 5t LXe
- Proposed LAr: DarkSide 20 t LAr, DEAP 50 t LAr
- Design & R&D studies: DARWIN 30-50 t LXe; ARGO 300 t LAr

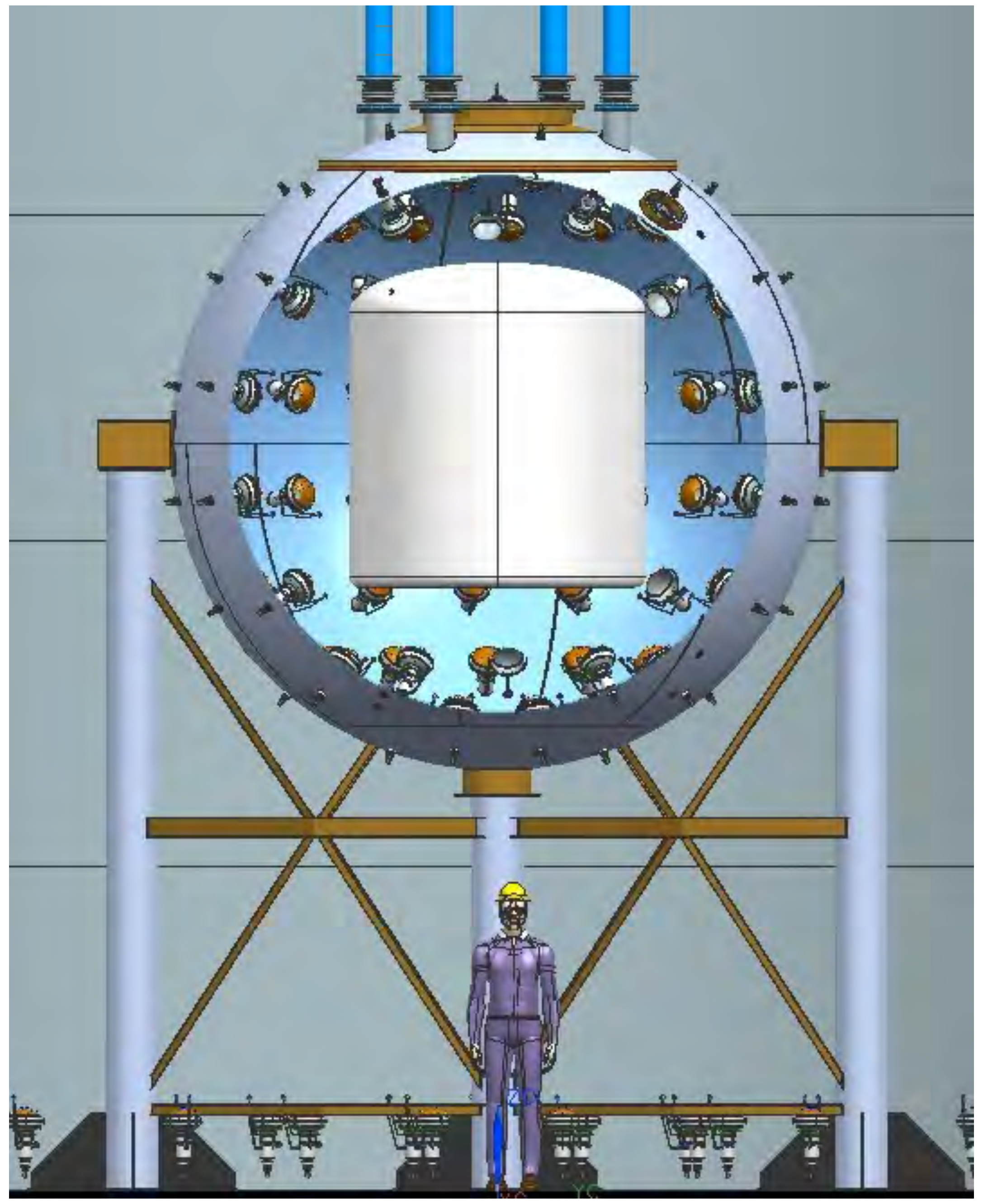
DARWIN: 50 t LXe



LZ: 7t LXe



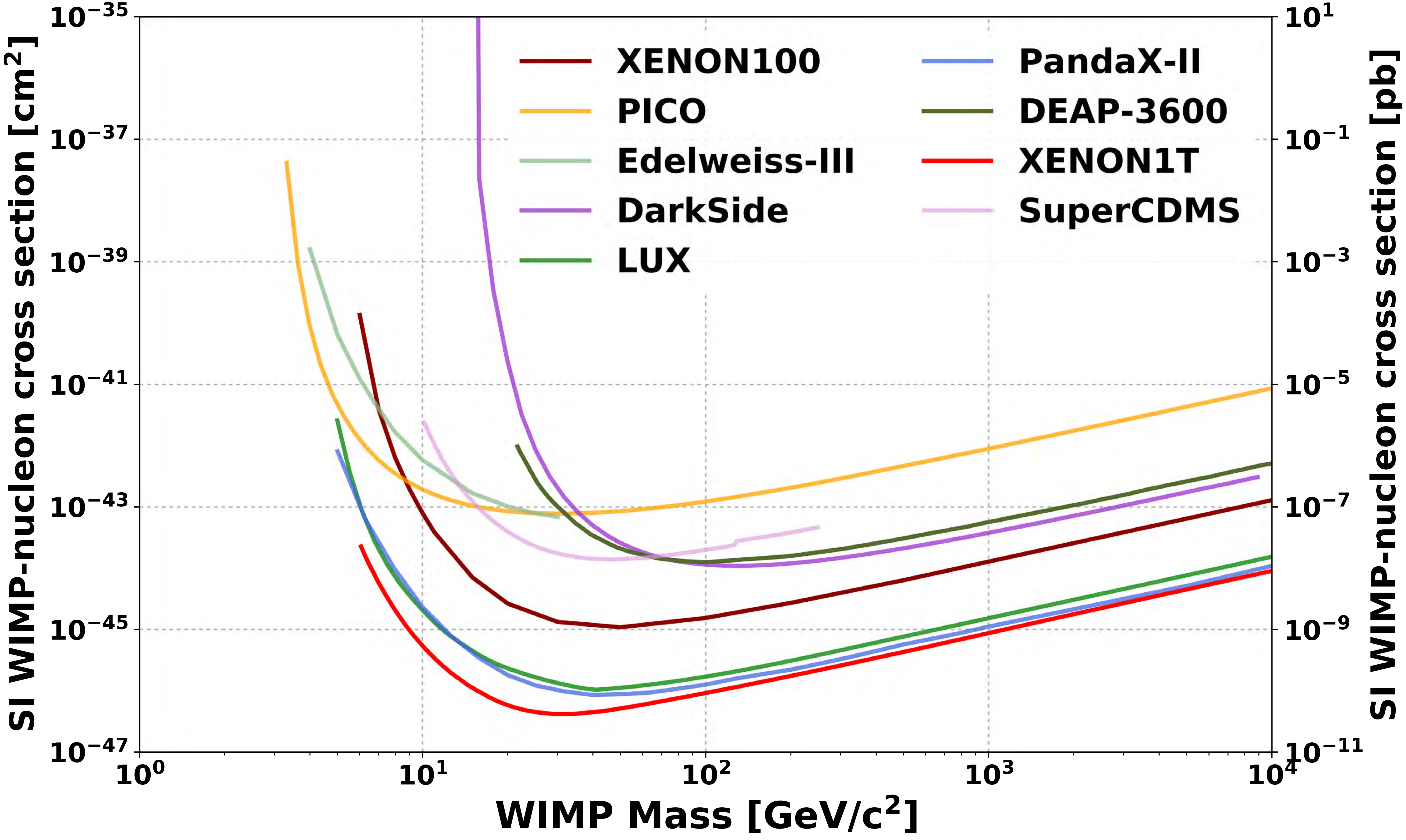
XMASS: 5t LXe



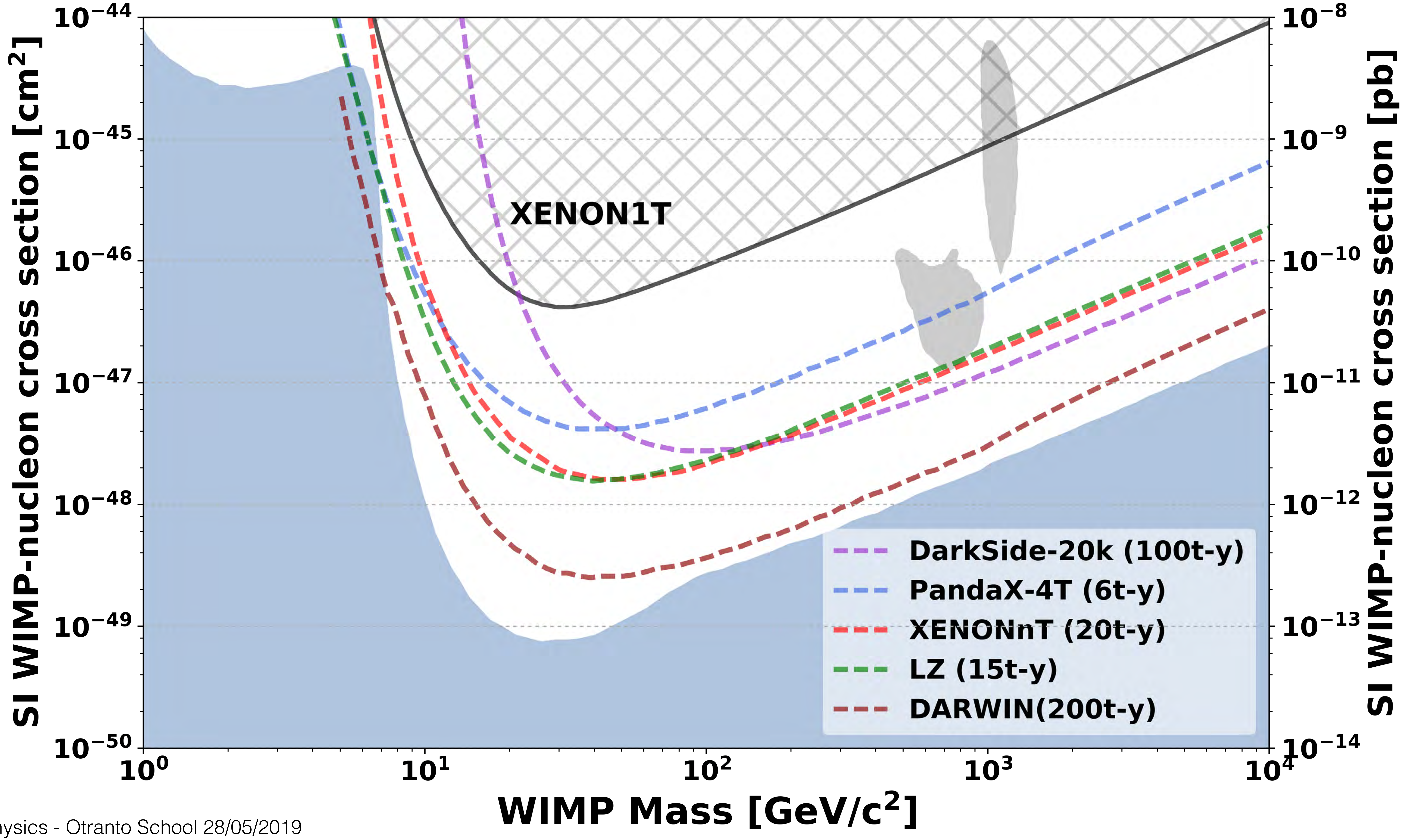
DarkSide: 20 t LAr

XENON1T: 3.3 t - LXe

Heavy WIMP's status



Heavy WIMP's perspectives



Double beta decay

ββ decay

Rare nuclear decay between isobar nuclei with |ΔQ|=2

Even-even nuclei: **ONLY** direct $0^+ \rightarrow 0^+$ transition

Different modes:

- (A,Z) → (A,Z+2) + 2e– + 2$\bar{\nu}$ (2νββ)
  - Standard 2nd order weak nuclear transition
  - Long lifetime ($10^{18\text{-}24}$ yr)
- **(A,Z) → (A,Z+2) + 2e⁻ (0νββ)**
  - Lepton number violation (LNV): physics beyond the SM

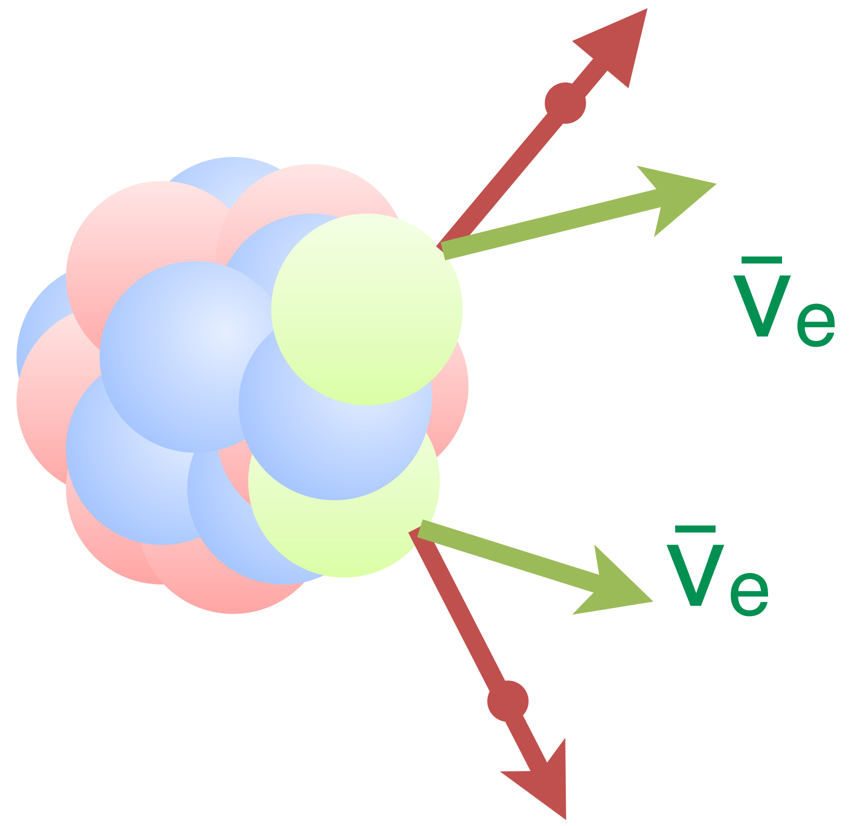
    Only possible if neutrinos are Majorana fermions

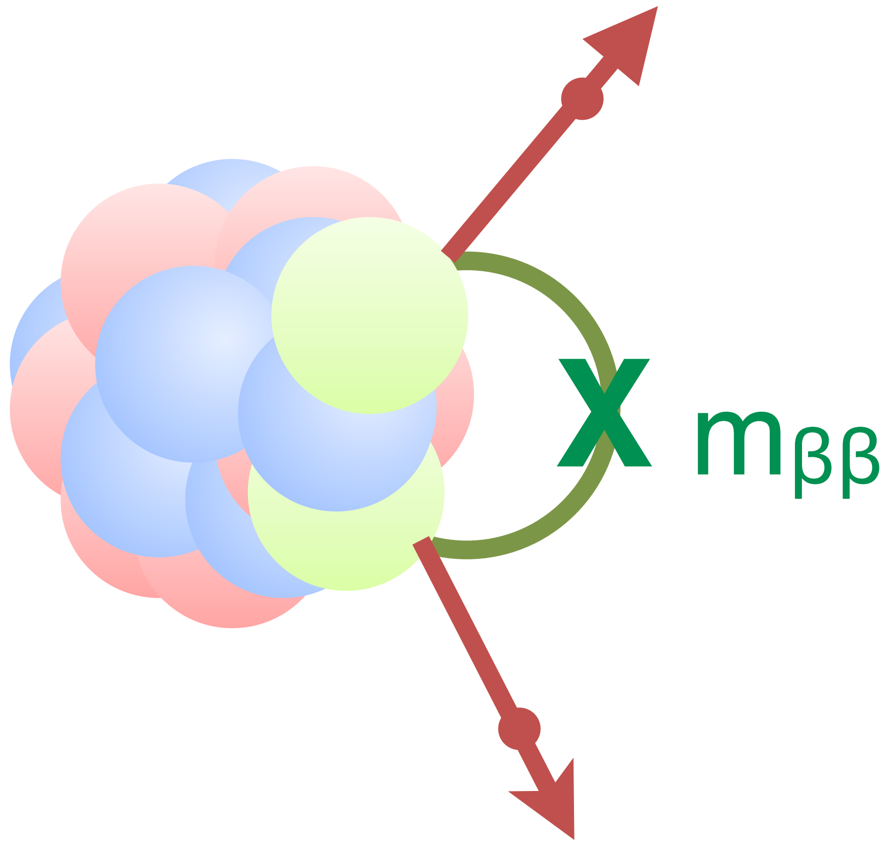
    → LNV (ΔL=2)

    → absolute neutrino mass scale

    → Majorana phases

    SM extensions
- (A,Z) → (A,Z+2) + nχ (exotic modes)





0νββ decay width

Under non trivial approximations it is possible to separate atomic, nuclear and particle contributions and factoring the transition width as

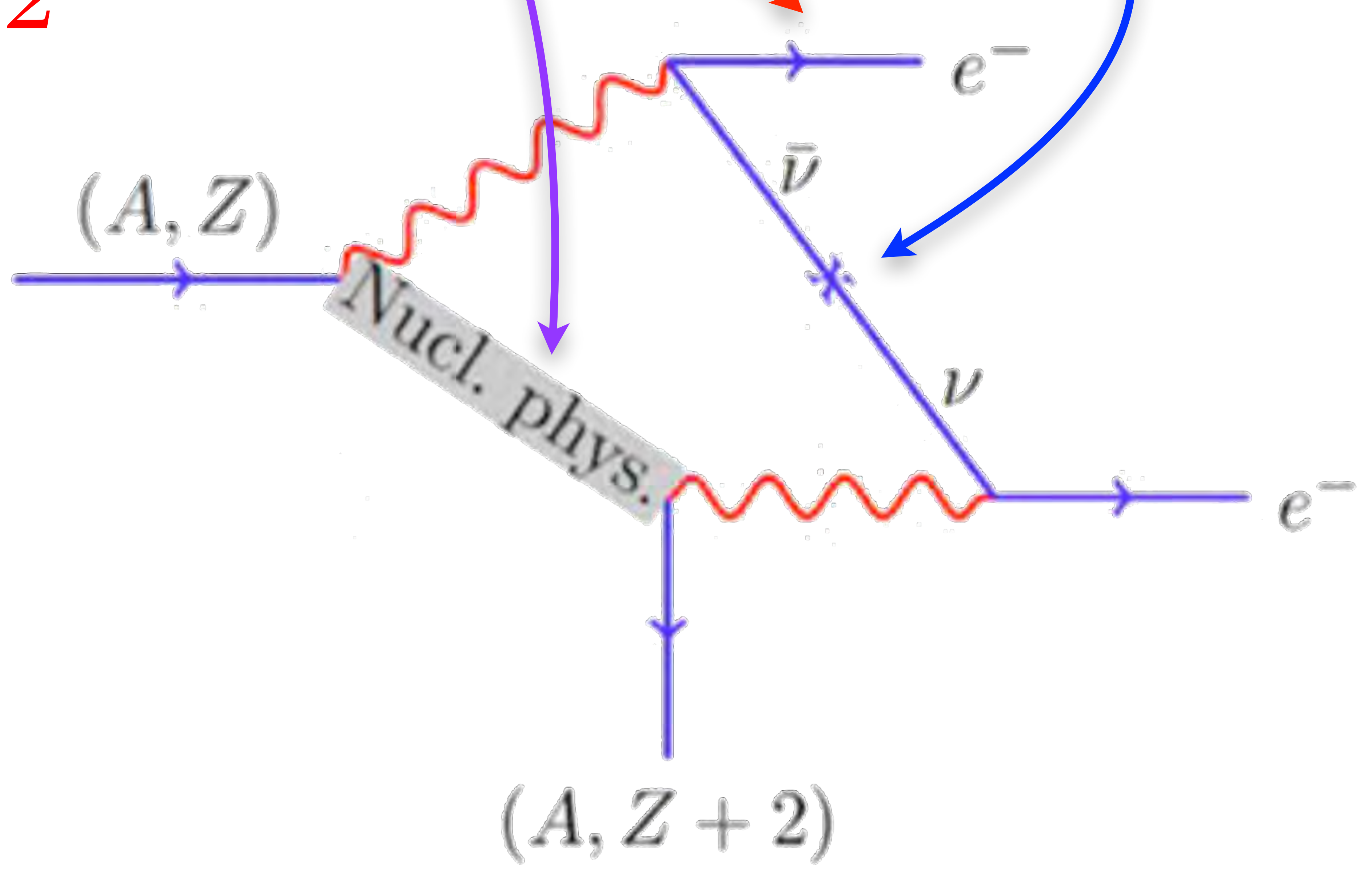
$$\Gamma^{0\nu} = G_x(Q,Z)|M_x(A,Z)|^2|\eta_x|^2$$

$G_x(Q,Z)$ = phase space factor ➝ precisely calculable

$M_x(A,Z)$ = nuclear matrix element ➝ problematic

η_x = particle physics parameter ➝ model dependent

- massive Majorana neutrinos
- GUT's
- SUSY
- …

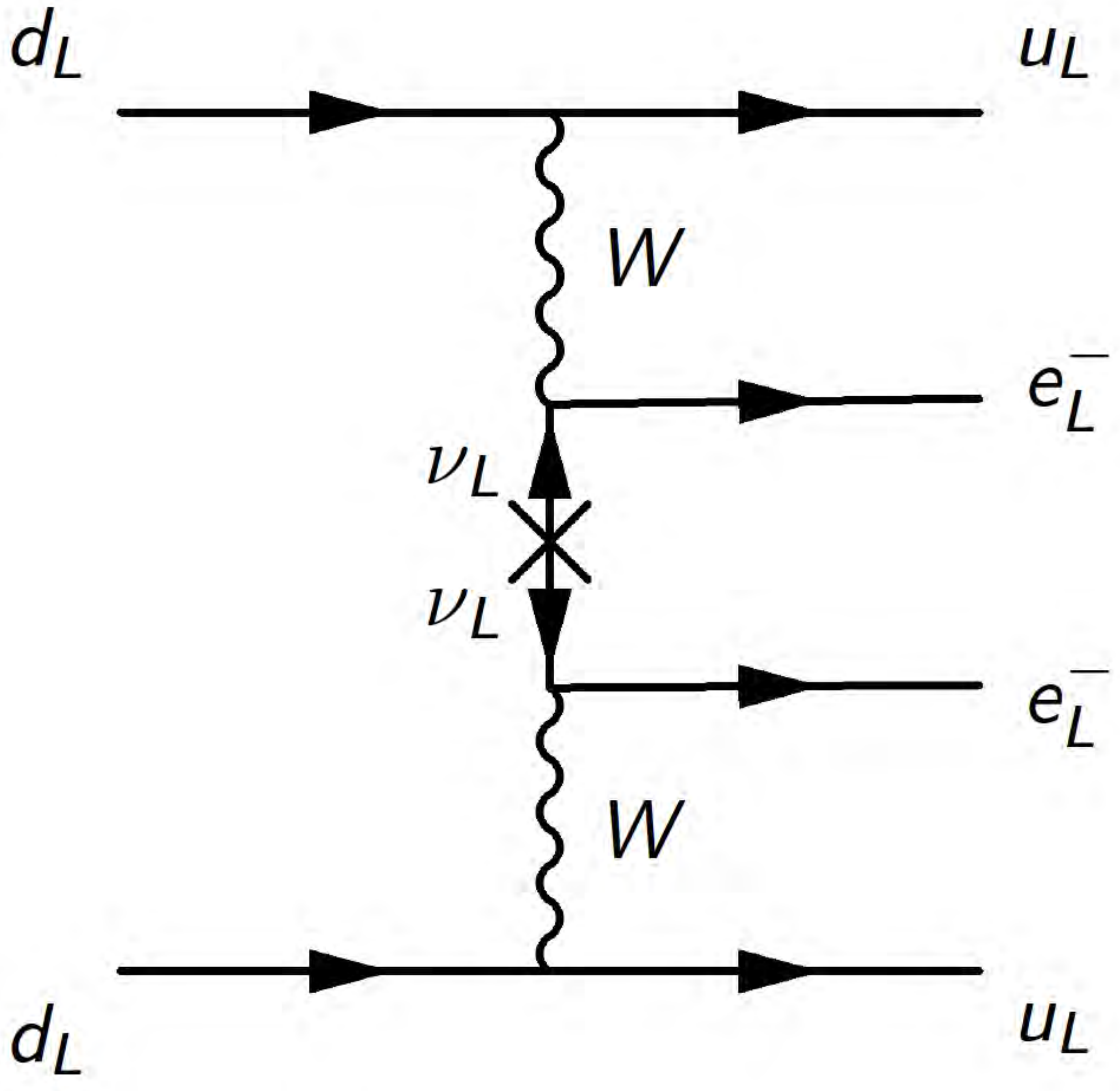


Lepton number violation (LNV) and

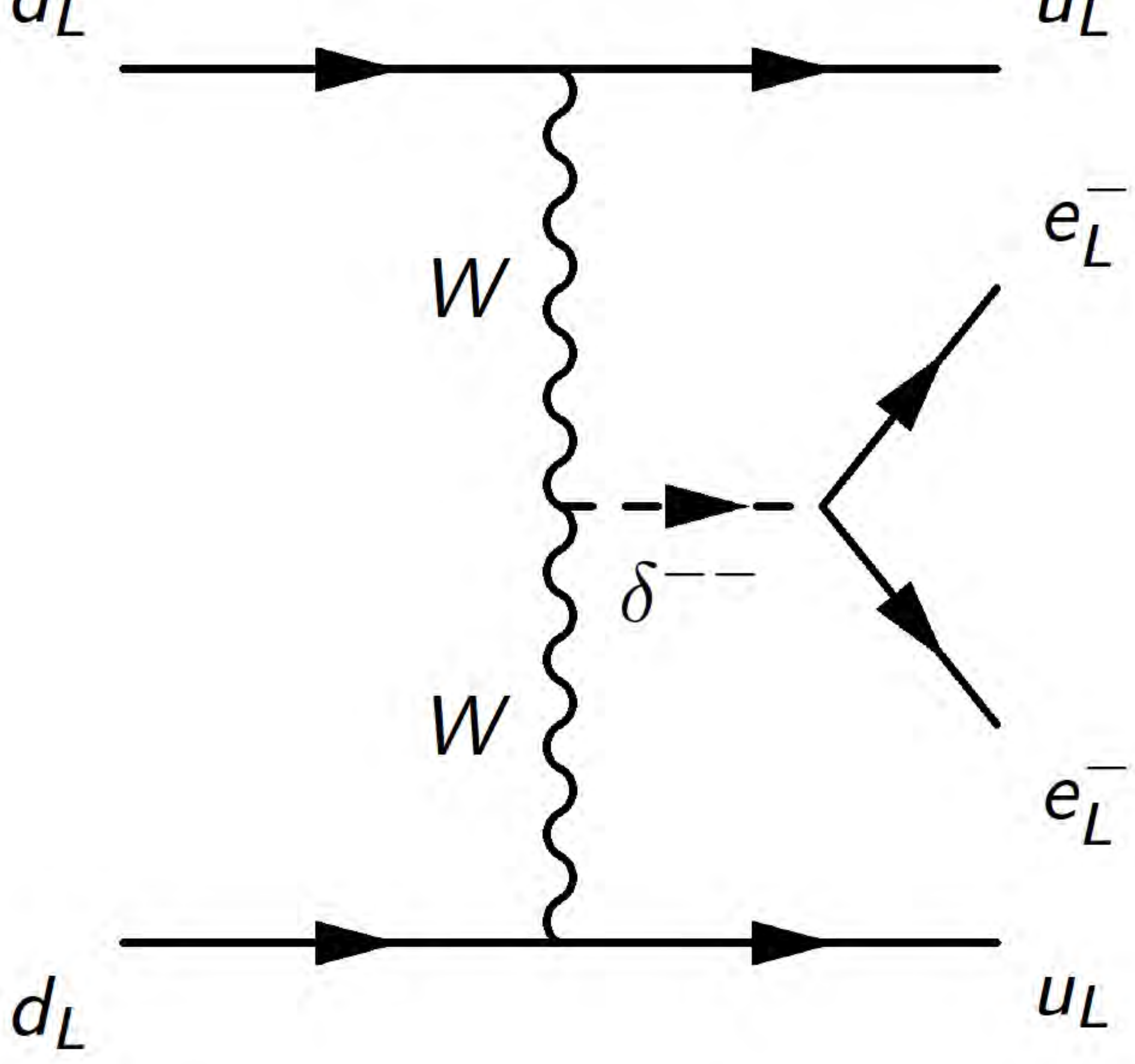
$A_{\beta\beta} \sim m_{ee}$

$A_{\beta\beta} \sim$ LNV parameters

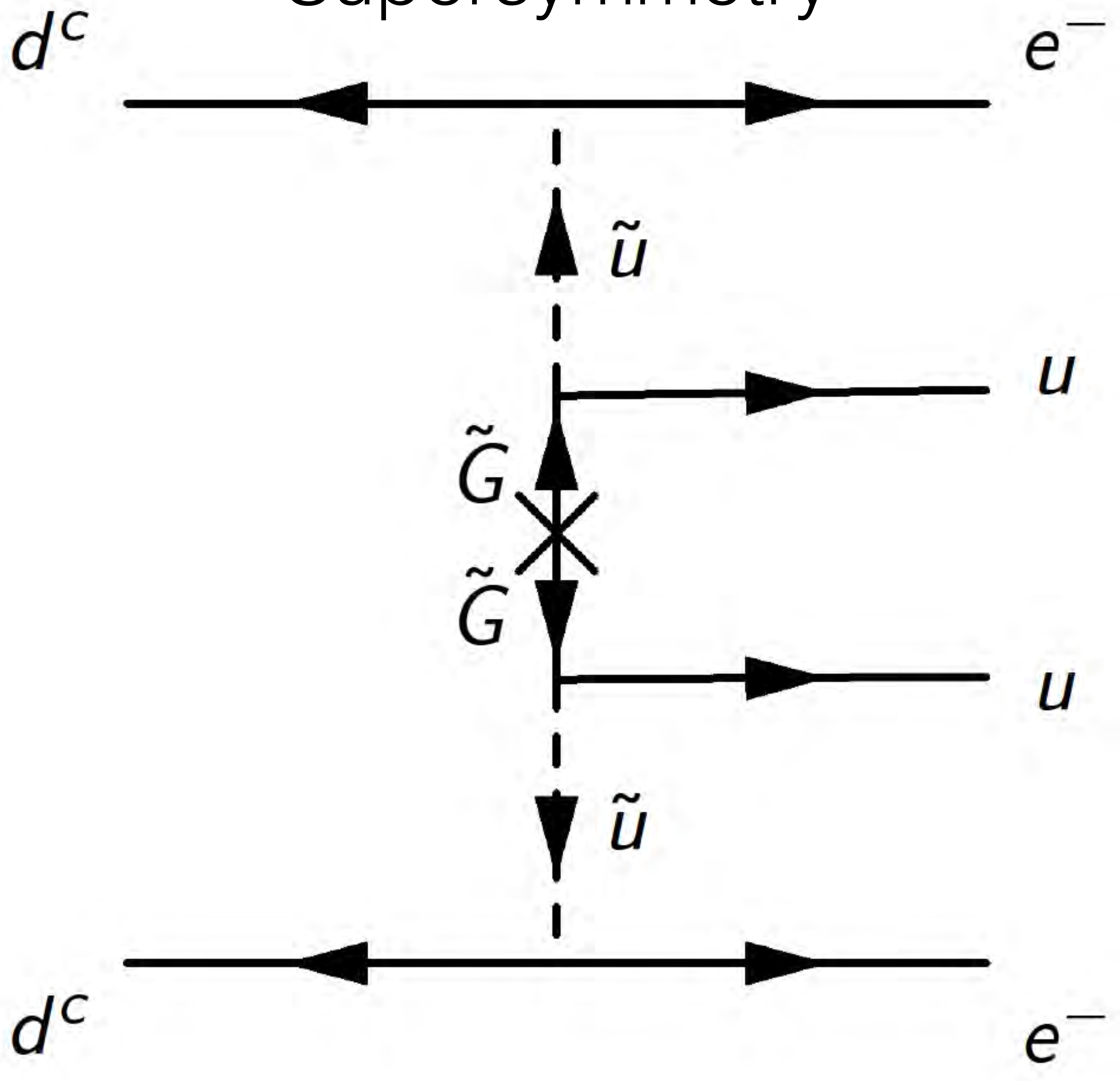
Mass mechanism



Higgs triplet model

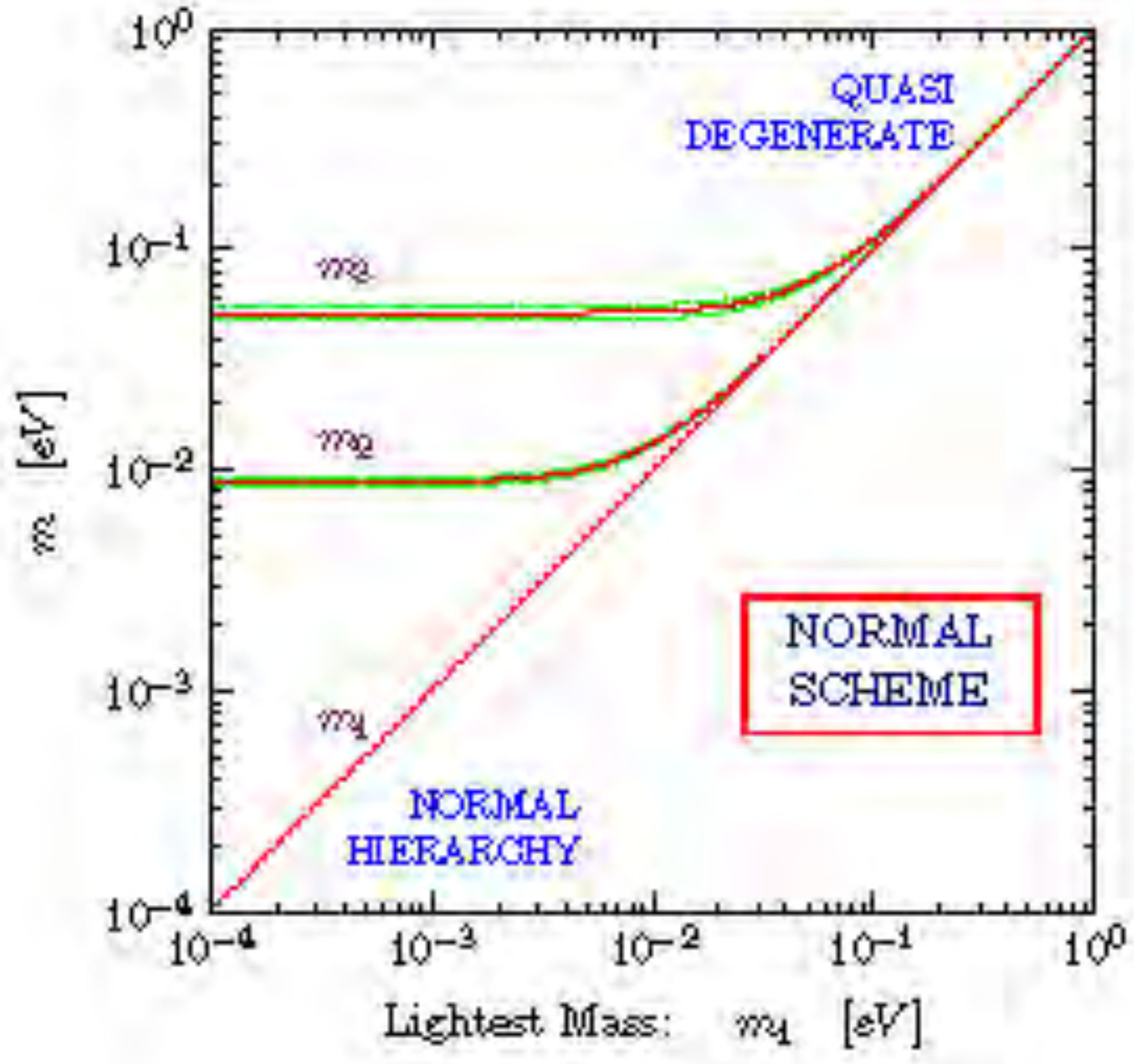


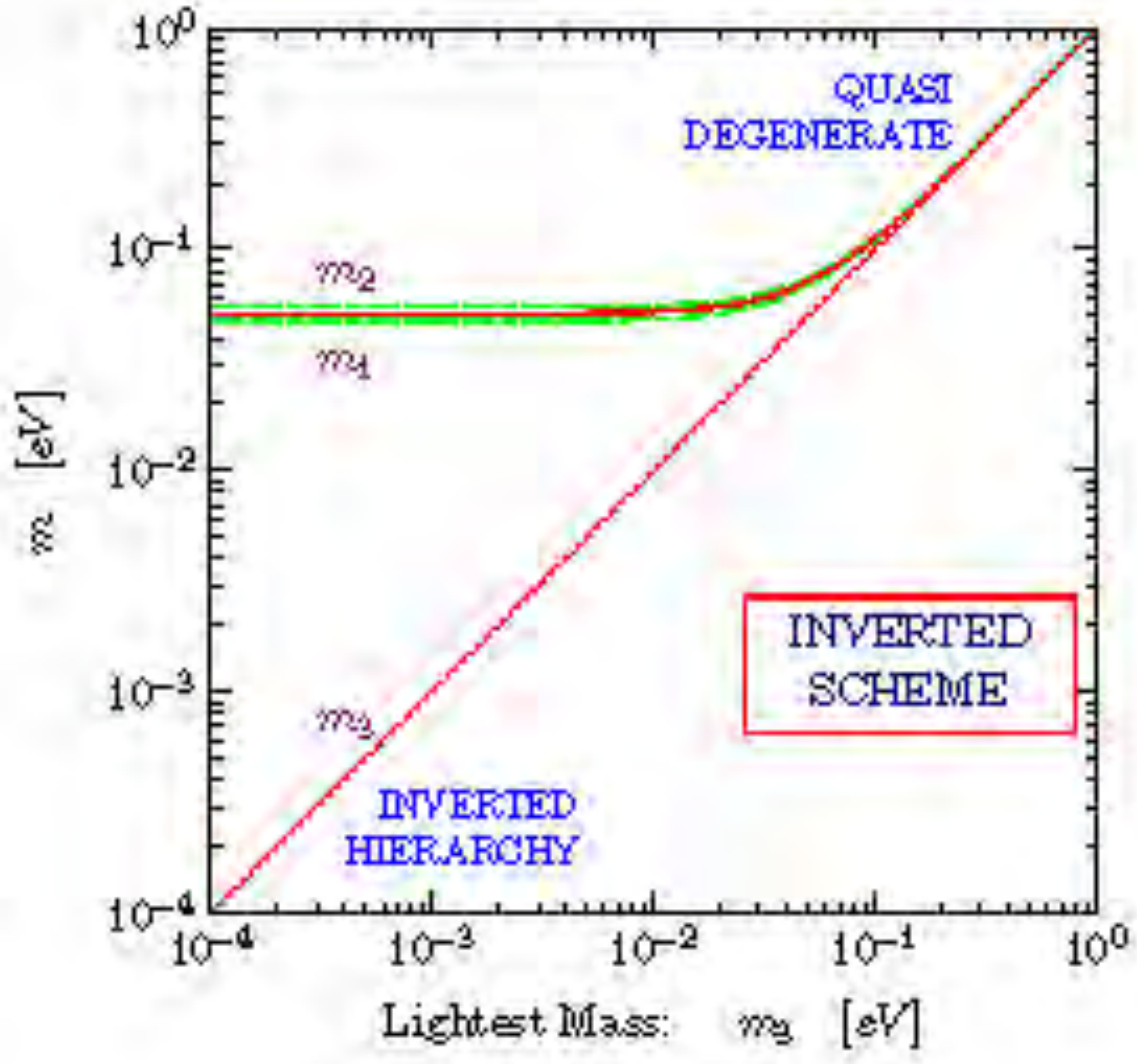
Supersymmetry



neutrino mass scale

- ν oscillations constrain neutrino mixings and mass splittngs but not the absolute mass scale.
- lightest neutrino mass (**m_1**) can be taken as free parameter





- however, the lightest neutrino mass is **not** really an “observable”

neutrino mass scale

- three realistc observables to probe ν masses

β decay:

- $m^2_i \neq 0$ can affect spectrum endpoint.
- sensi0ve to the "effective electron neutrino mass":

$$m_\beta = \sqrt{c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2}$$

0νββ decay:

- can occur if $m^2_i \neq 0$ and $\nu=\overline{\nu}$ (Majorana, not Dirac)
- sensi0ve to the "effec0ve Majorana mass" (and phases):

$$m_{\beta\beta} = | c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3^2 e^{i\phi_3} |$$

Cosmology:

- m2 i ≠ 0 can affect large scale structures in (standard) cosmology
- constrained by CMB + other data
- Sensi0ve to:

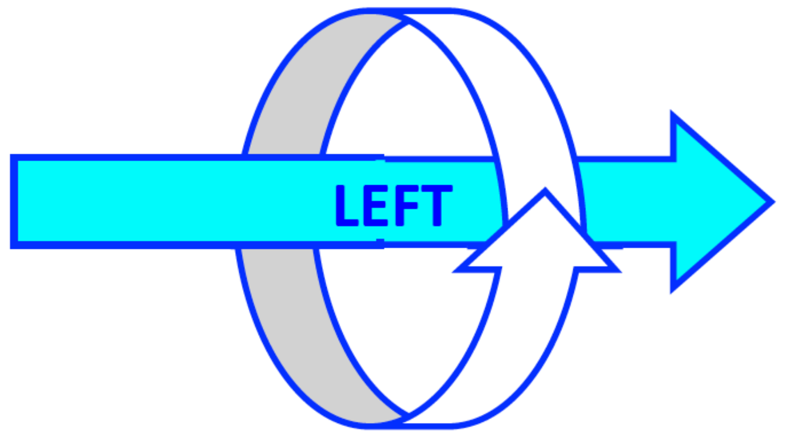
$$\Sigma = m_1 + m_2 + m_3$$

neutrinoless double beta decay basics

- Weak interactions (CC) are chiral (= not mirror-symmetric) → V-A

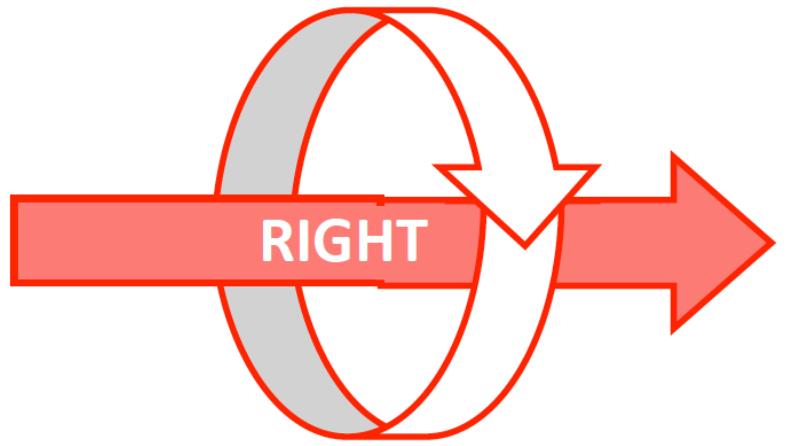
➡ ν are created with left-handed (LH) chirality

ν



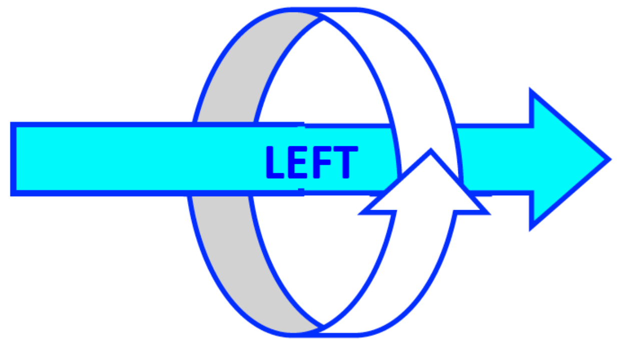
➡ $\bar{\nu}$ are created with right-handed (RH) chirality

$\bar{\nu}$

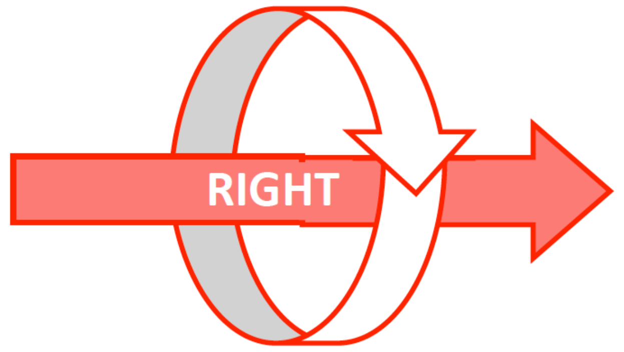


- for **massless ν** chirality is a constant of motion
  - 2 independent d.o.f.: massless (Weyl) spinor
  - helicity = chirality

ν



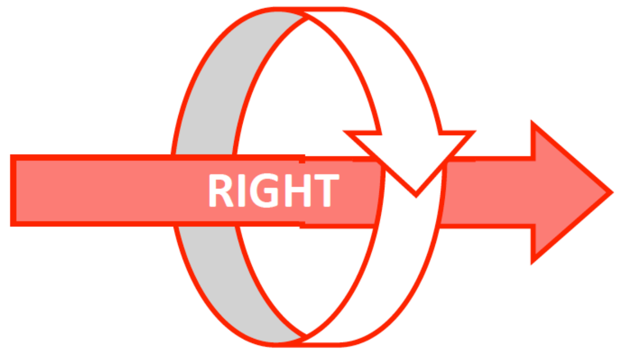
$\bar{\nu}$



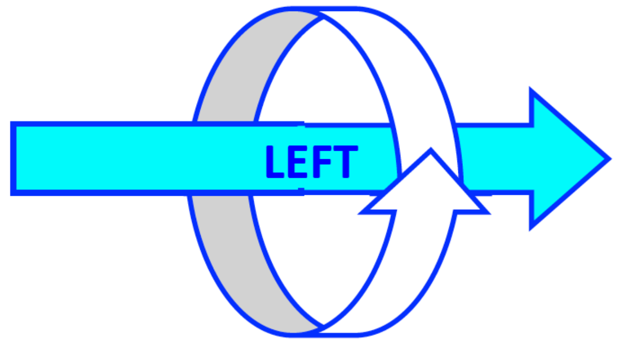
+ O(m/E)

- **massive ν** can develop a “wrong” handedness at O(m/E) (the Dirac equation mixes RH and LH states for mν≠0):

$\bar{\nu}$



ν



DIRAC picture
- the 4 d.o.f. are independent
- massive 4-spinor
- $\nu \neq \bar{\nu}$ as for electrically charged fermions
- can define a “lepton number”

MAJORANA picture
- only 2 d.o.f. are independent
- massive 2-spinor
- $\nu = \bar{\nu}$
- “lepton number” violated by 2 units

for neutral leptons 2 components (same chirality) can coincide

lepton number vs handedness

- let's define ν ($\bar{\nu}$) as the neutral lepton emitted in β+ (β) decay

$$(A, Z) \rightarrow (A, Z-1) + e^{+} + \nu$$

$$(A, Z) \rightarrow (A, Z+1) + e + \bar{\nu}$$

- based on the fact that the following reactions have been experimentally observed

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

- while the following reactions have never been experimentally observed

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

➡ neutrinos are Dirac fermions

➡ a (conserved) lepton number selects possible reactions (ΔL=0 the first 2 reactions, ΔL=2 the latter)

- however a consistent picture is possible also in the Majorana case (ΔL=2)

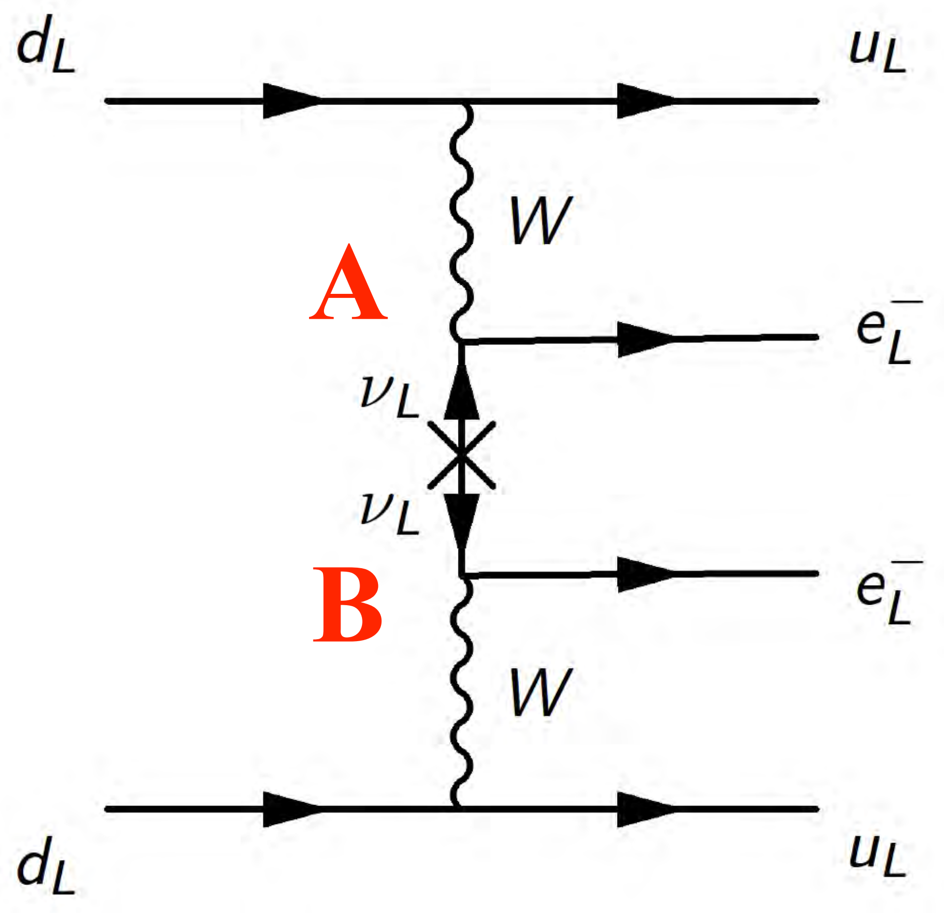
m=0 ➡ ν ($\bar{\nu}$) is always associated with the negative (positive) charged lepton

m>0 ➡ ν ≡ LH $\bar{\nu}$ ≡ RH

➡ pure ν state (β+ decay) can develop a RH component at O(m/E)

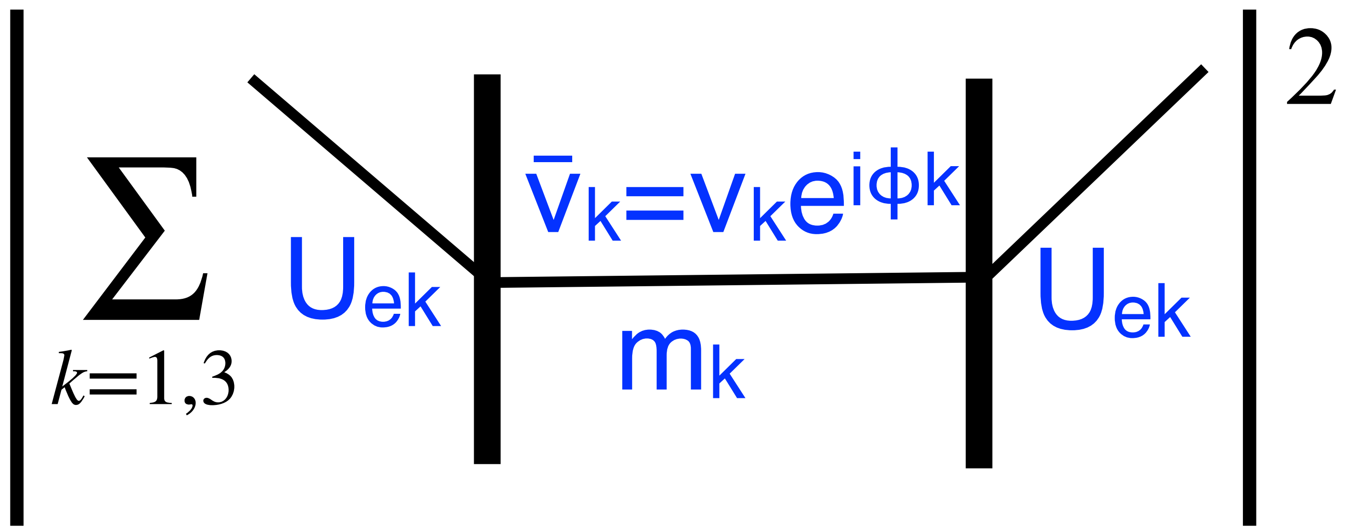
➡ ΔL≠0 possible @ O(m/E) (very small!!!)

$0\nu\beta\beta$ decay (NDBD)



- A RH an0neutrino is emitted at vertex “A” together with an electron
- If it is massive, at O(m/E) it develops a LH component (not possible if Weyl)
- If $\nu=\bar{\nu}$, this component is a LH neutrino (not possible if Dirac)
- **The LH (Majorana) neutrino is absorbed at “B”** where a 2nd electron is emitted

- ν’s are mixed. We must sum over the mixed stated to get the decay probability



$$\propto \left| \sum_{k=1}^{3} U_{ek}^2 m_k e^{i\varphi_k} \right| \equiv m_{\beta\beta}^2$$

- only 2 out of 3 Majorana phases are independent ….

Schechter-Valle theorem ("black box")

[Schechter and Valle, 1982]

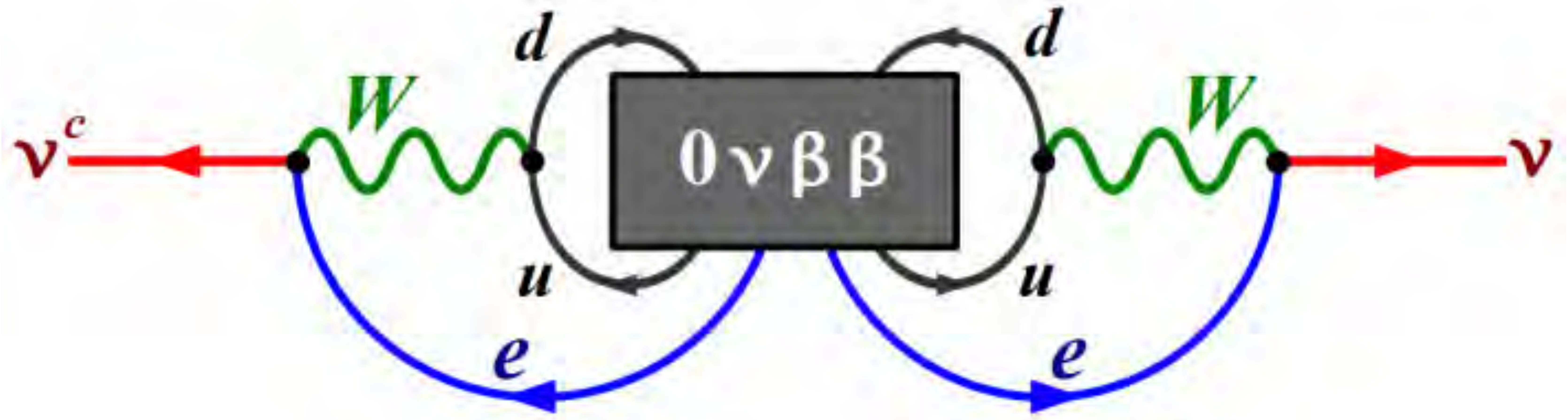
A non-zero *0νββ* amplitude implies a non vanishing Majorana neutrino mass

Basic assumptions:

- massive electron and u and d quarks
- standard left-handed interactions

Taking into account present 0νββ upper limits the conclusion is that the Feynman graph below corresponds to an unobservably small neutrino Majorana mass: $\mathbf{m_{bb} \sim 10^{-25}}$ **eV**

[Duerr M., Lindner M. & Merle A. J. High Energ. Phys. (2011) 2011:9; arXiv:11105.0901]



Majorana vs Dirac in oscillations

- The mixing matrix for Majorana ν's is

$$U \to U \cdot U_M \qquad U_M = \mathrm{diag}(1, \mathrm{e}^{\mathrm{i}\varphi_2}, \mathrm{e}^{\mathrm{i}\varphi_3})$$

with the usual 2 independent Majorana phases

- In the Hamiltonian for neutrino oscillations (both vacuum and matter) the mixing matrix always appears in the form

$$U \frac{M^2}{2E} U^\dagger \qquad M^2 = \mathrm{diag}(\mathrm{m}_1^2, \mathrm{m}_2^2, \mathrm{m}_3^2)$$

- The replacement $U \to U \cdot U_M$ is therefore ineffective

$$U \frac{M^2}{2E} U^\dagger \quad \to \quad U U_M \frac{M^2}{2E} U_M^\dagger U^\dagger = U \frac{M^2}{2E} U^\dagger$$

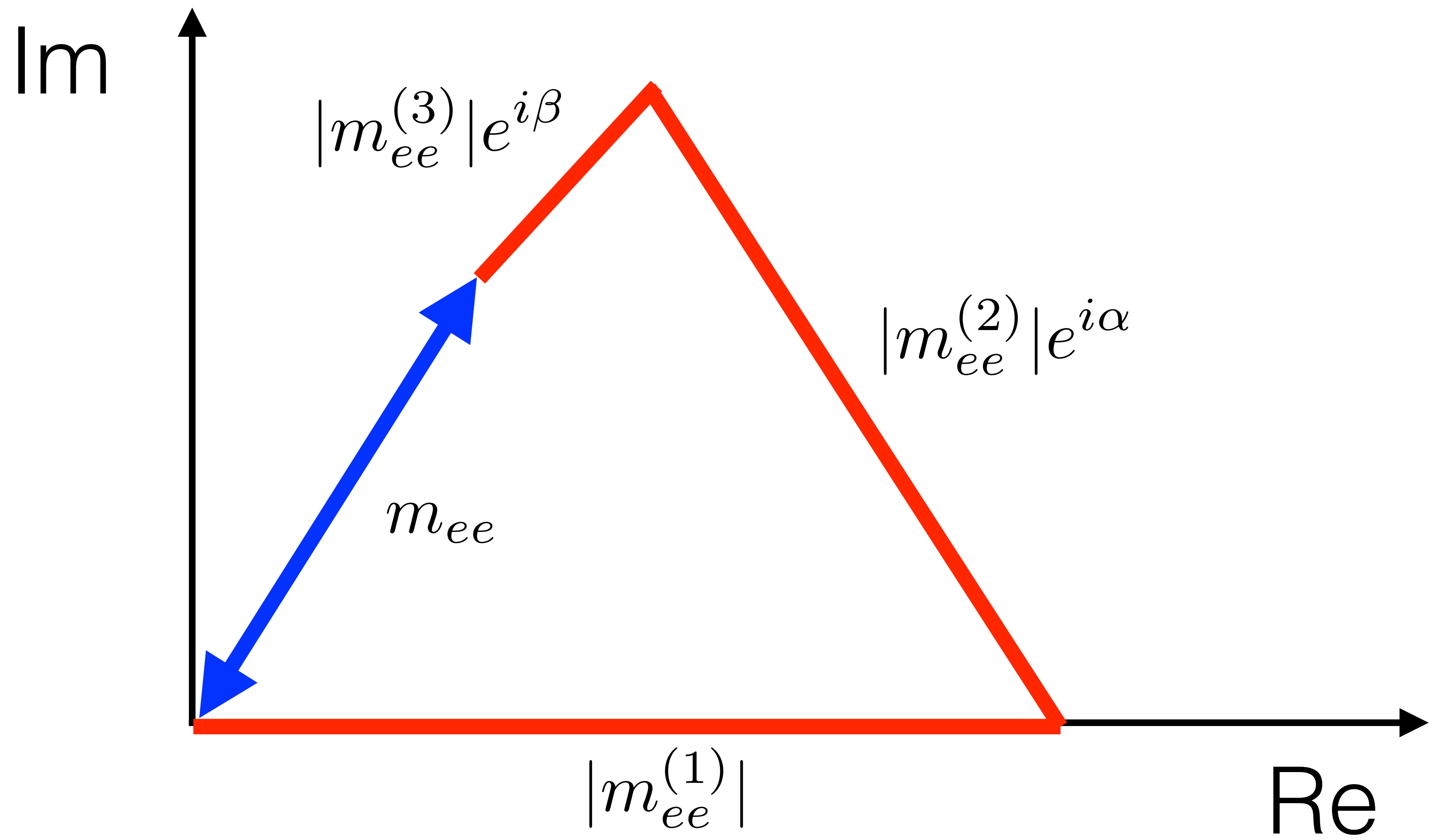
and oscillations can't distinguish Dirac/Majorana neutrinos

ββ0ν standard interpretation: light

- Neutrinoless Double Beta Decay is mediated by light massive Majorana neutrinos and all other potential mechanisms give negligible or no contribution

$$\eta_x = < m_{ee} >= \sum_k U_{ek}^2 m_k$$
$$= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

- The transition amplitude is proportional to coherent sum of neutrino masses
- Majorana phases play a crucial role: possible cancellations

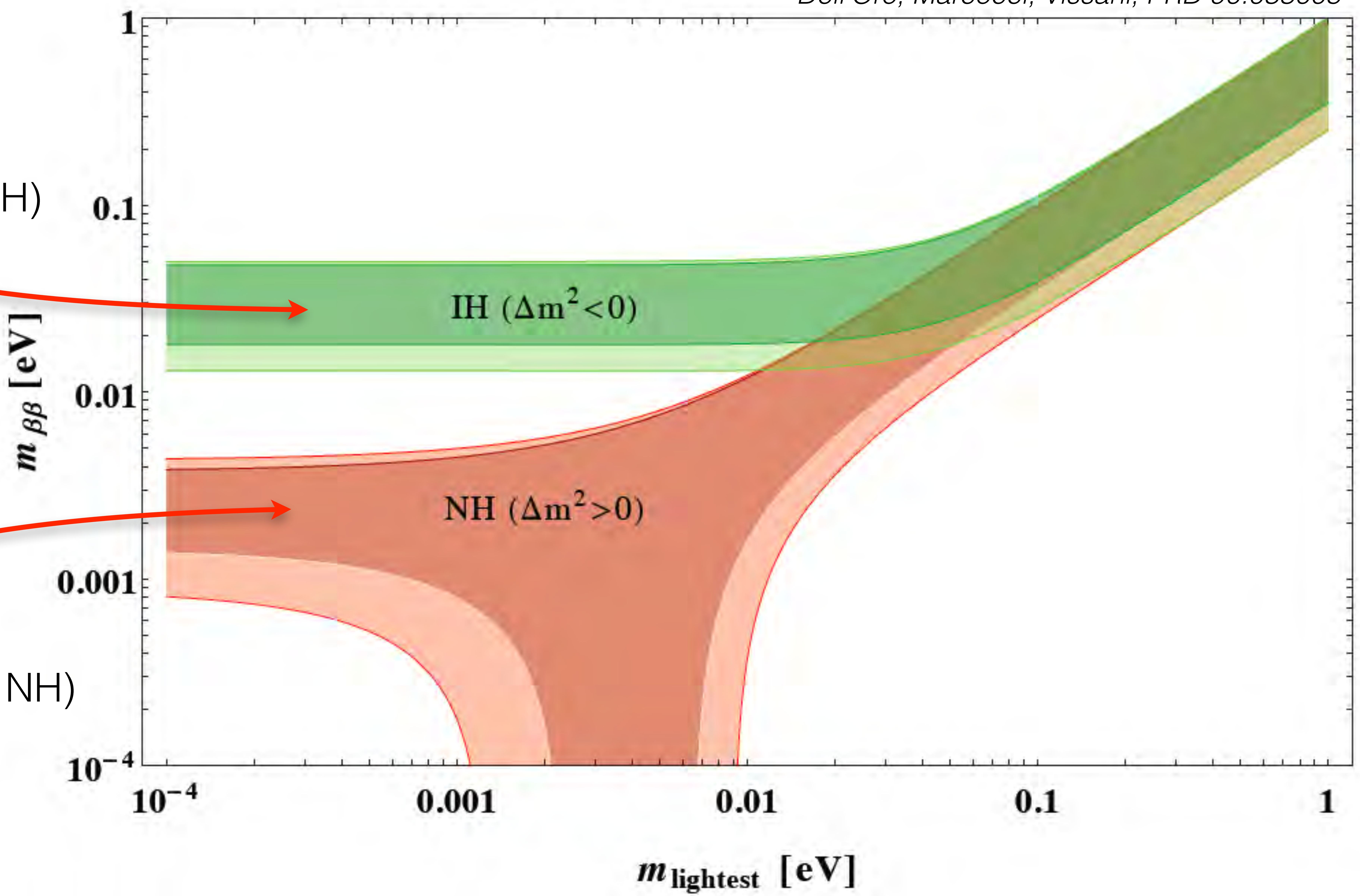


Light Majorana neutrino

Dell'Oro, Marcocci, Vissani, PRD 90.033005

Inverse Ordering (IO or IH)

Normal Ordering (NO or NH)



Distinguishing 0νββ mechanisms

A single measurement of total rate cannot pin down underlying 0νββ mechanisms.

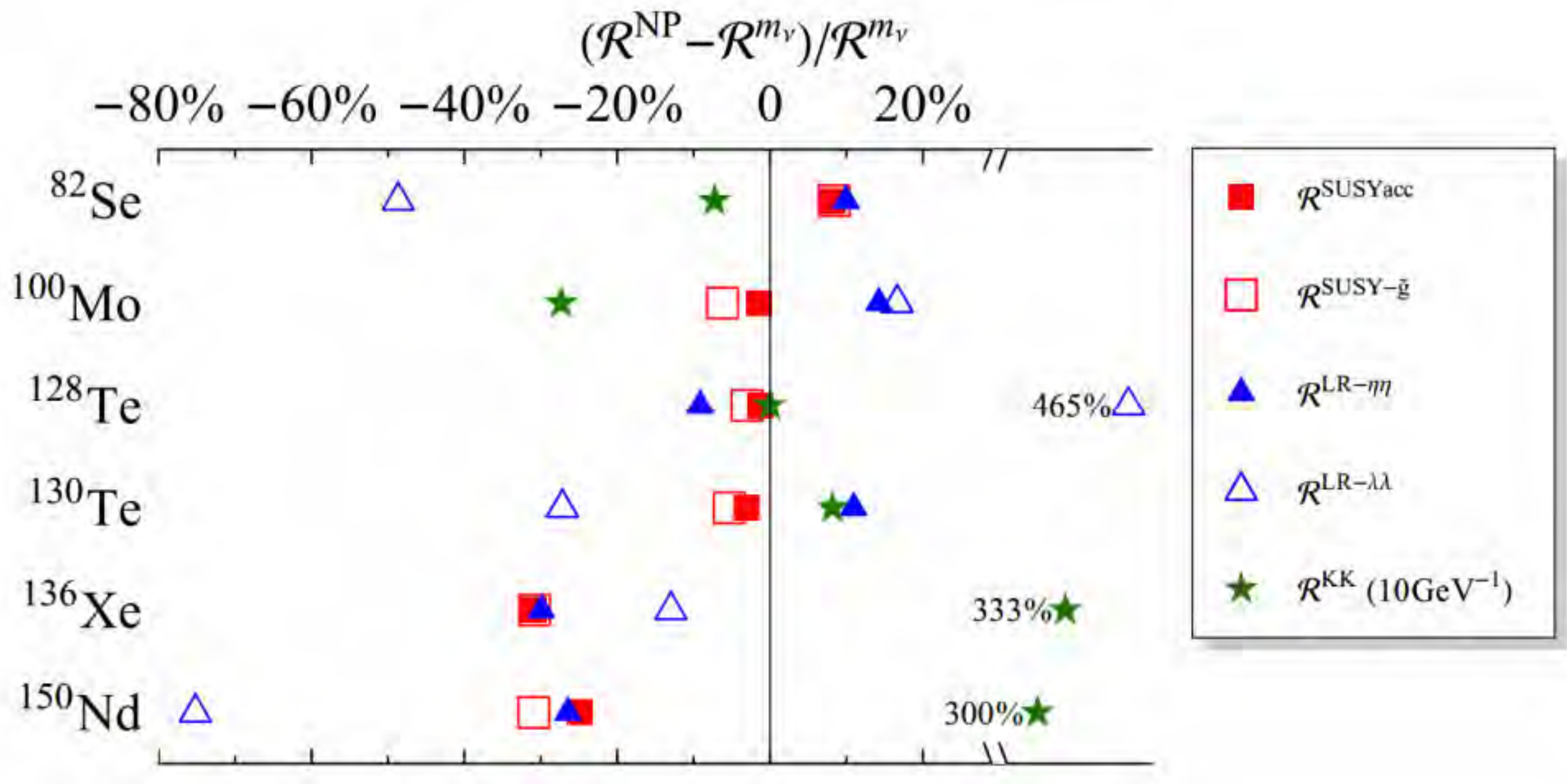
- Half life ratios of different isotopes

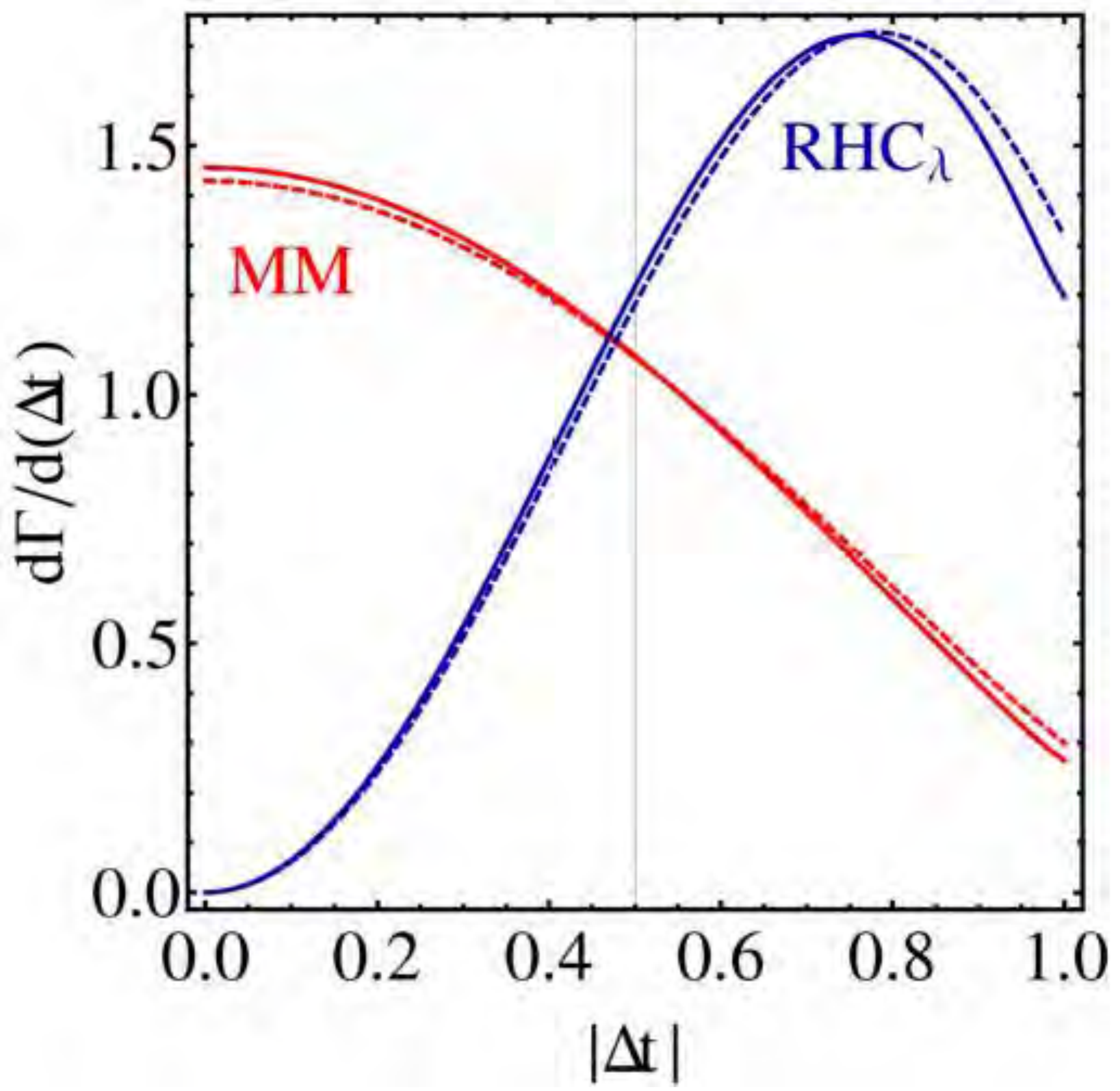
  Deppisch,Päs 06 , Gehman,Elliot 07 , Fogli,Lisi,Rotunno 09
- Electron angular correlations

  Ali,Borisov,Zhuridov 07
- Decay to excited states and other rare decays

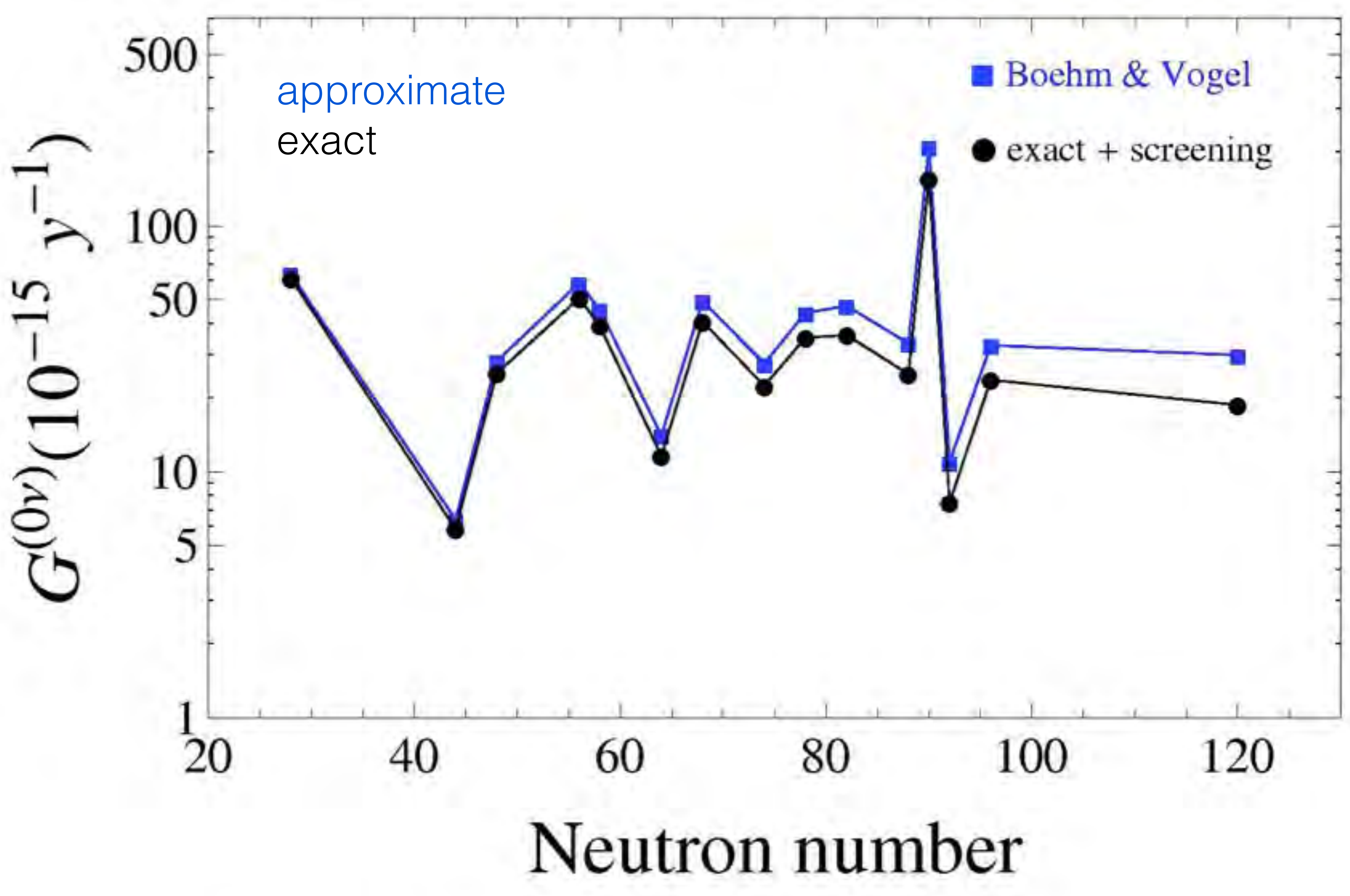
  Faessler et.al. 94
- LNV processes at the LHC

  Allanach,CHK,Päs 09





Extract m_{ee} from data: a hard job



F. Böhm and P. Vogel, *loc. cit.*

J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012)

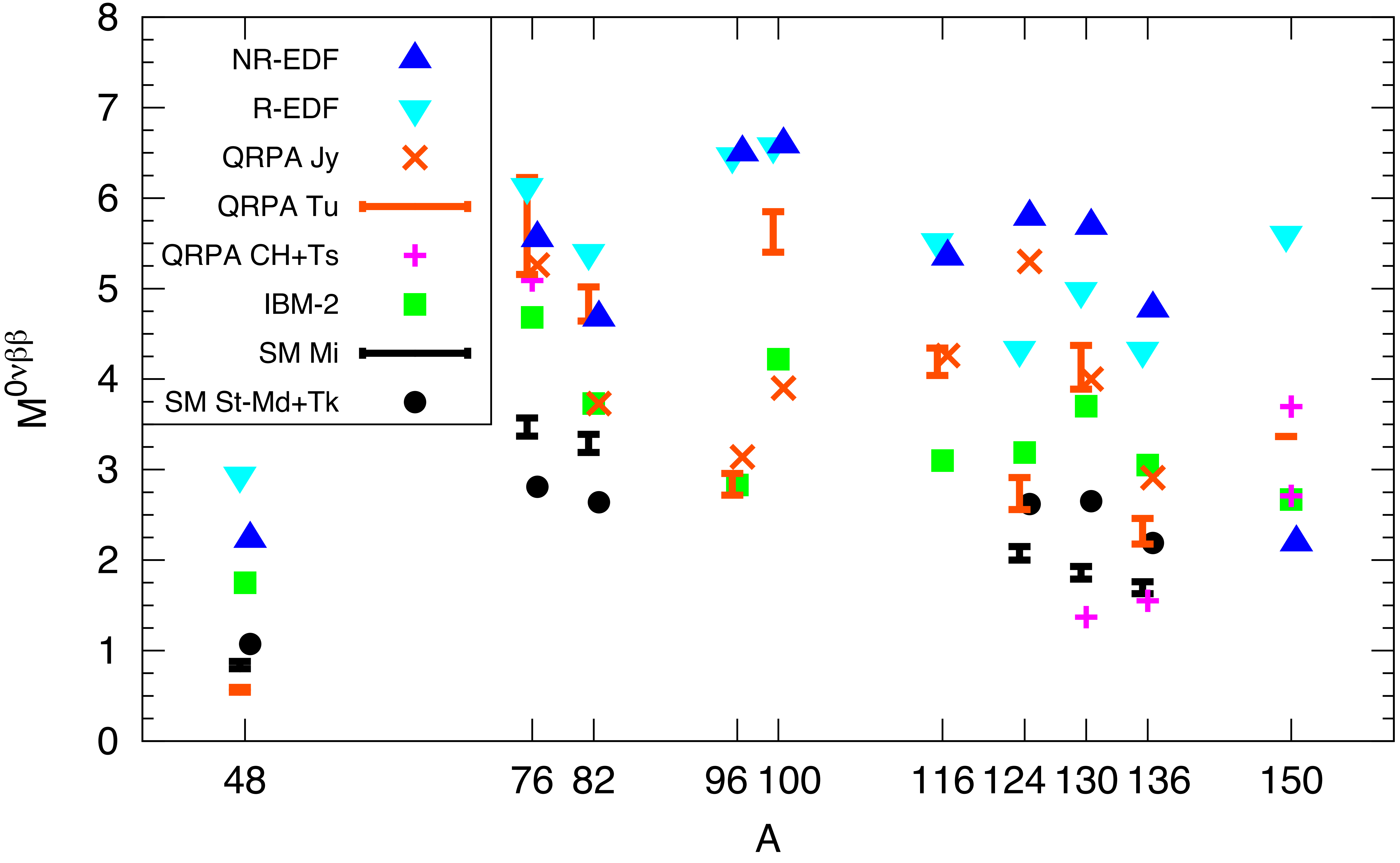
$$\Gamma^{0\nu} = G_{0\nu}(Q,Z)|M_{0\nu}(A,Z)|^2|m_{ee}|^2$$

The easy part:
phase space factor
→ precisely calculable

Extract m_{ee} from data: a hard job

Full estimated range of $M^{0\nu}$ within different calculation methods

$$\Gamma^{0\nu} = G_{0\nu}(Q,Z)|M_{0\nu}(A,Z)|^2|m_{ee}|^2$$



Jonathan Engel and Javier Menéndez 2017 *Rep. Prog. Phys.* **80**

Much more problematic: nuclear matrix elements

- Significant spread
- Absolute values inaccuracy

quenching of g_A?

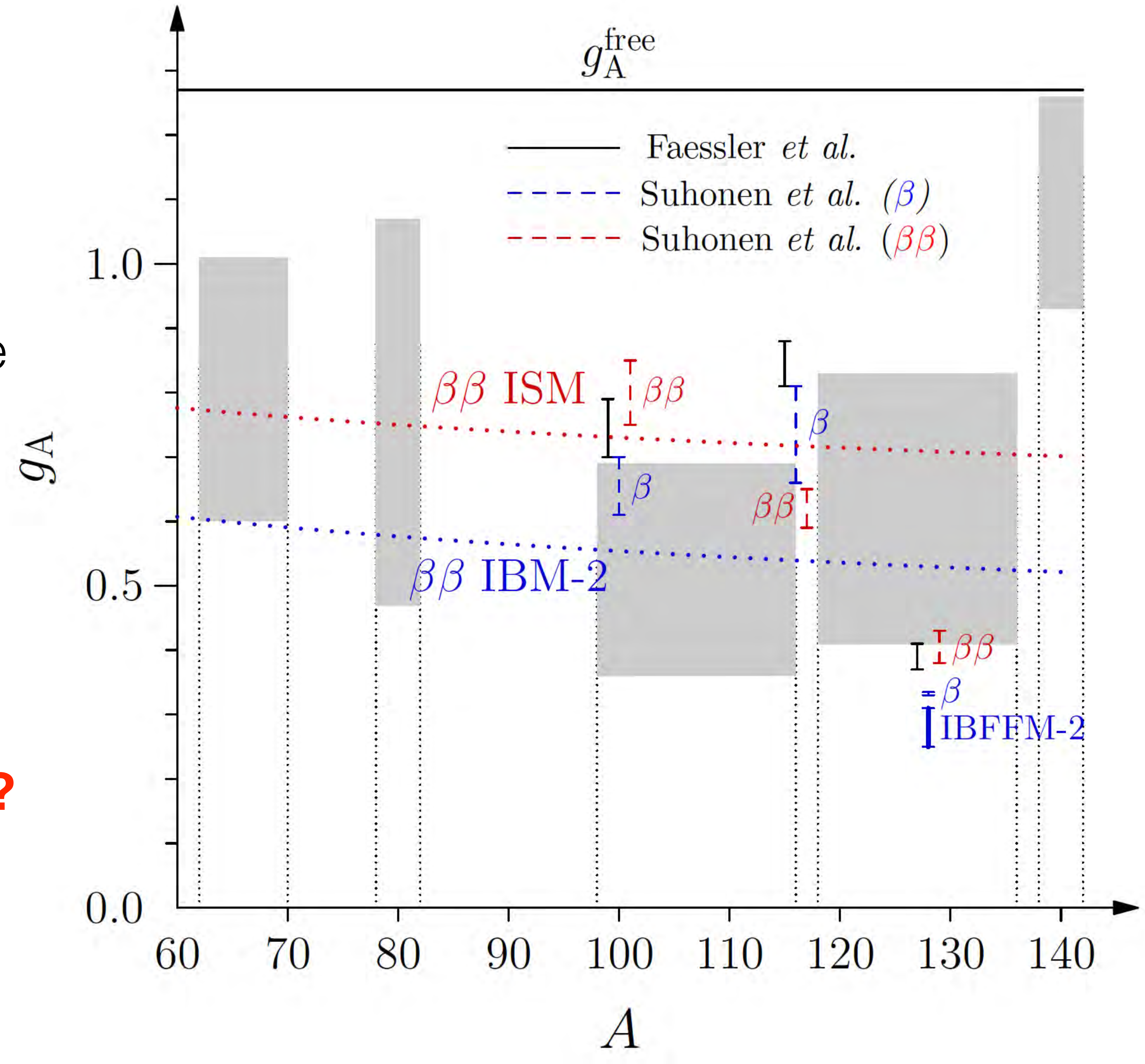
$\Gamma_{\beta\beta} \sim g_A^4$

gA quenching

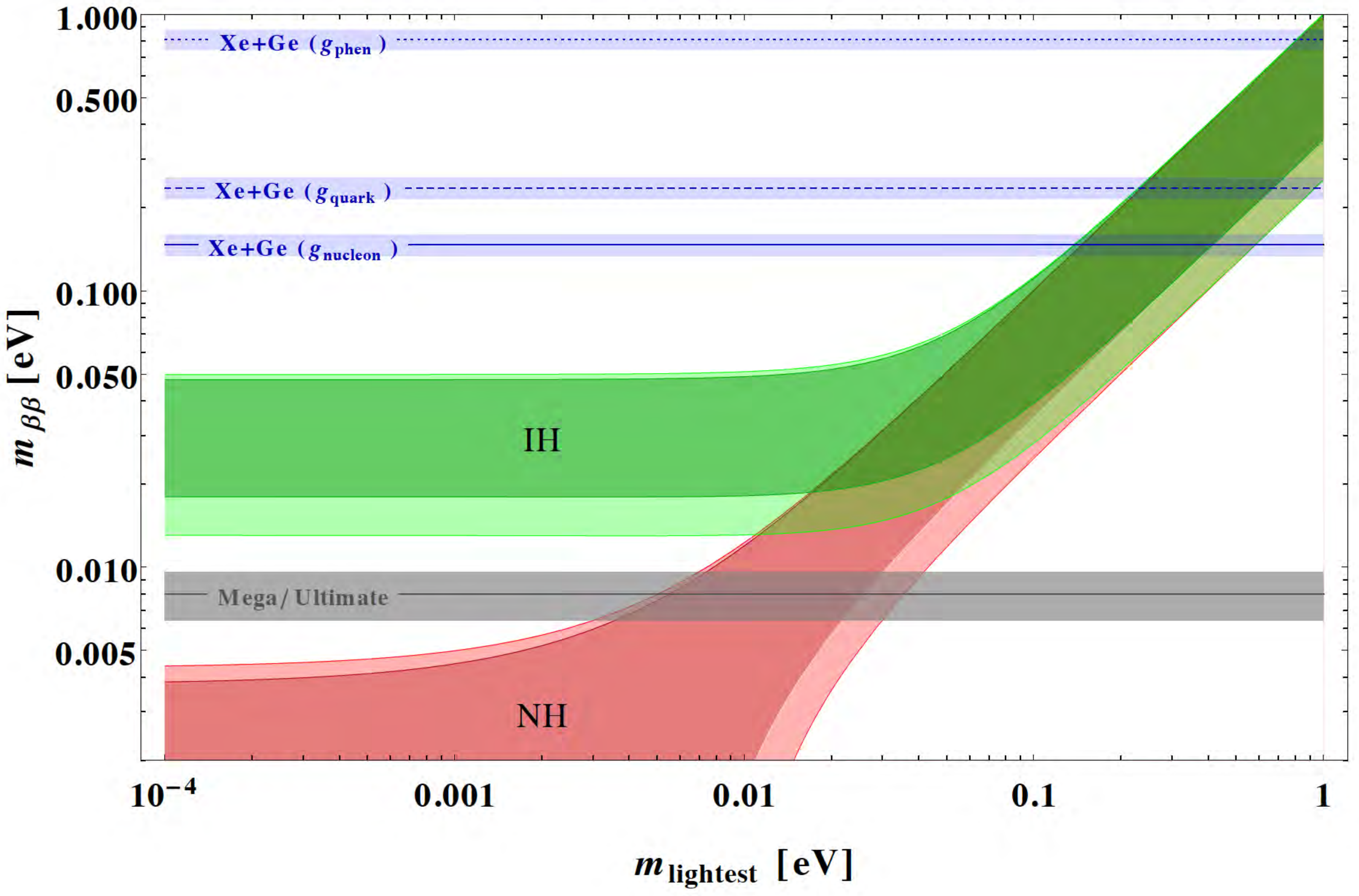
Allowed “beta” decays

- Recent analysis of pn-QRPA, ISM and IBM based calculations of single β and 2νββ decays shows evidence for an evident dependence of the g_A quenching on A (J.Suhonen, Neutrino 2018):

Mass range	76-82	100-116	122-136
g_A	0.7-0.9	0.5	0.5-0.7



Dell’Oro, Marcocci, Vissani arXiv:1404.2616



What about 0νββ?

Forbidden “beta” decays

- Possible extrapolation to 0νββ (large momentum transfer)
- Crucial role of high forbiddance non unique transitions

^{94}Nb, ^{98}Tc, ^{99}Tc, ^{113}Cd, ^{115}In, ^{138}Cs

Caveat: 0νββ decay is a high-momentum transfer process (q~100 MeV) → less quenching

Experimental signature

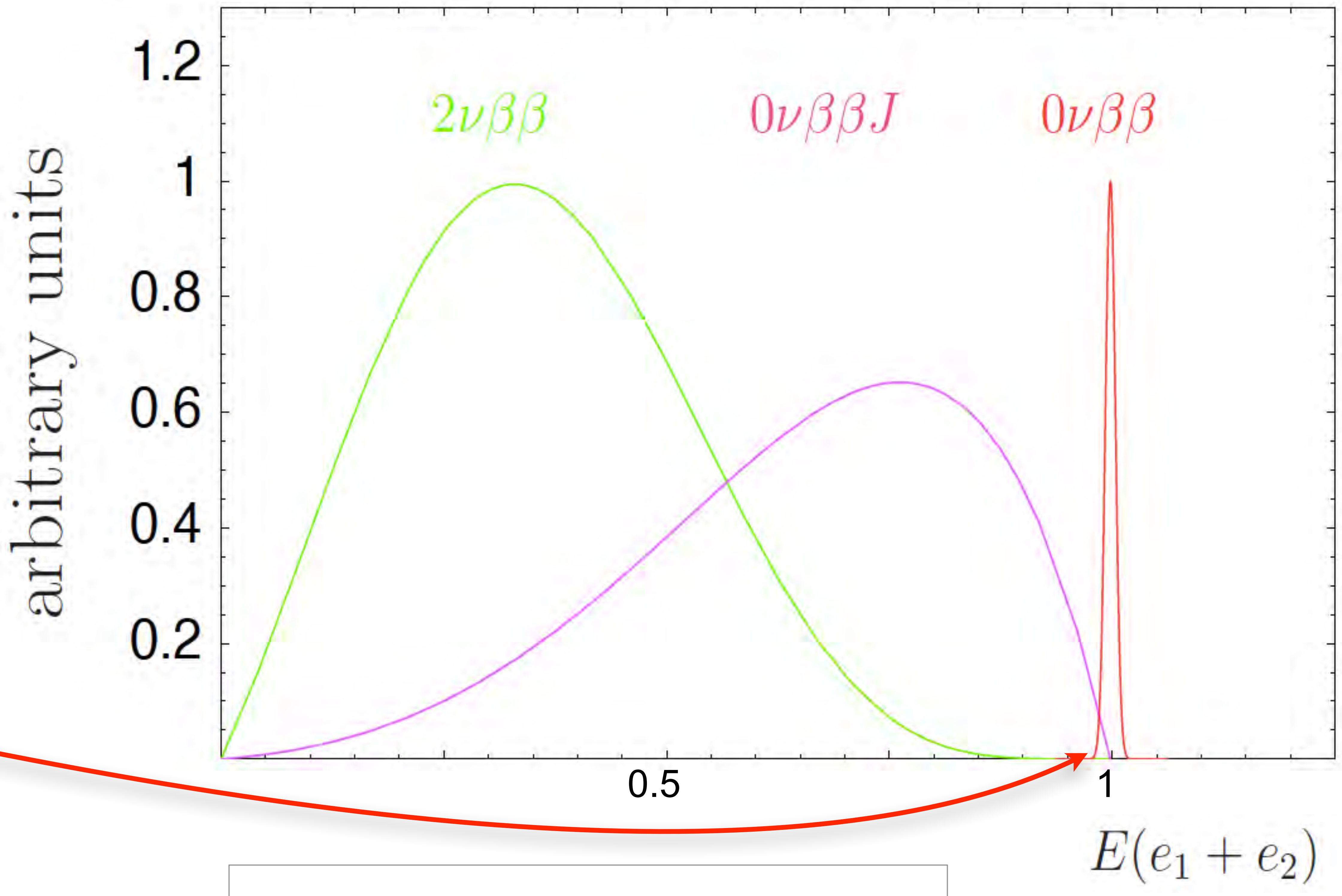
(A,Z) → (A,Z+2)$^{++}$ + 2 e-

- A new (ionised) isotope
- Two electrons

Minimal information:

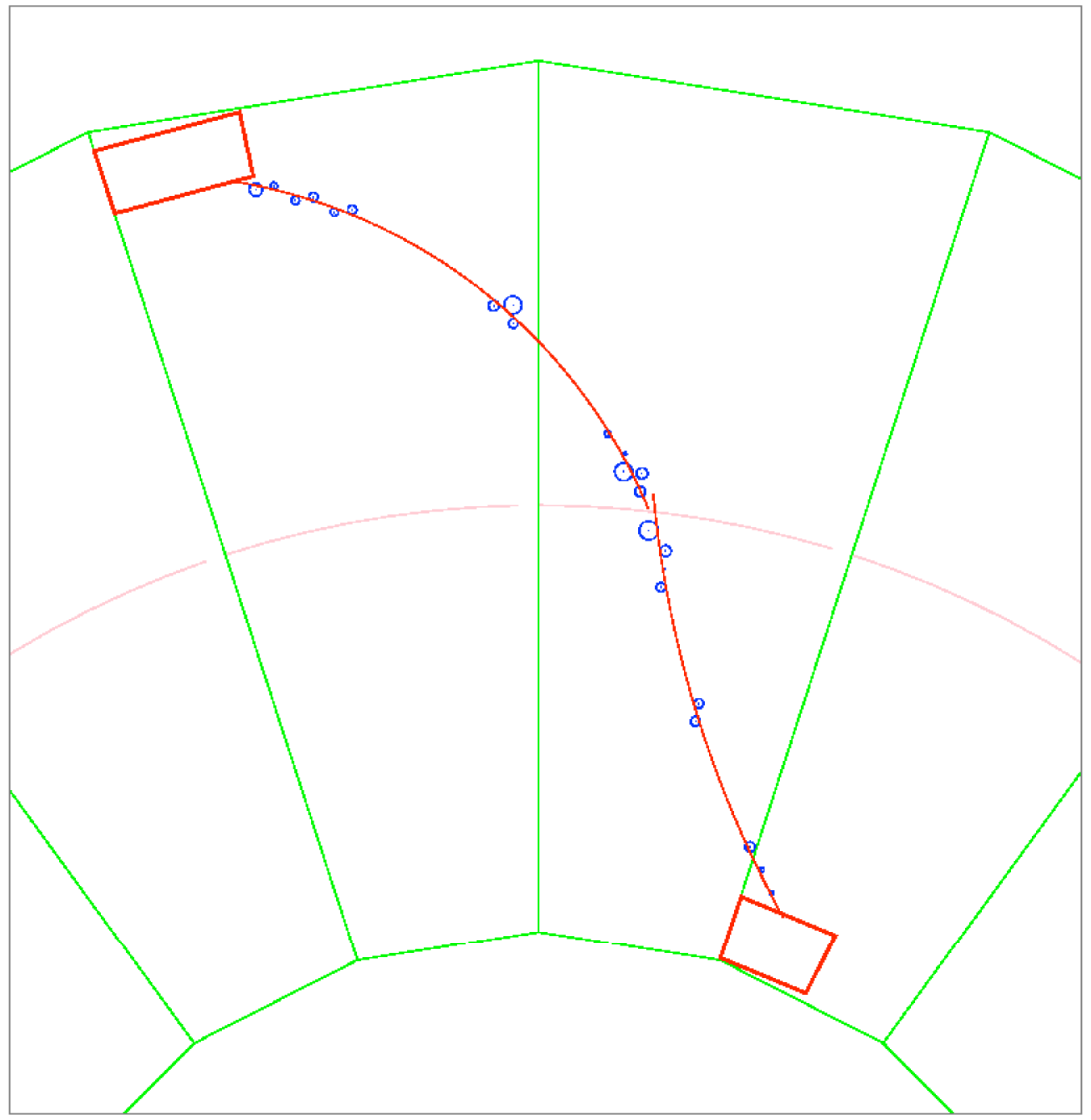
- two e^- energy sum spectrum (total deposited energy)

0νββ exhibits a peak at Q over 2νββ tail (and background contributions)



Additional signatures:

- Daughter nuclear species
- Single electron energy spectrum
- Angular correlation between the two electrons
  - → Track and event topology
  - → Time Of Flight



Two experimental approaches:

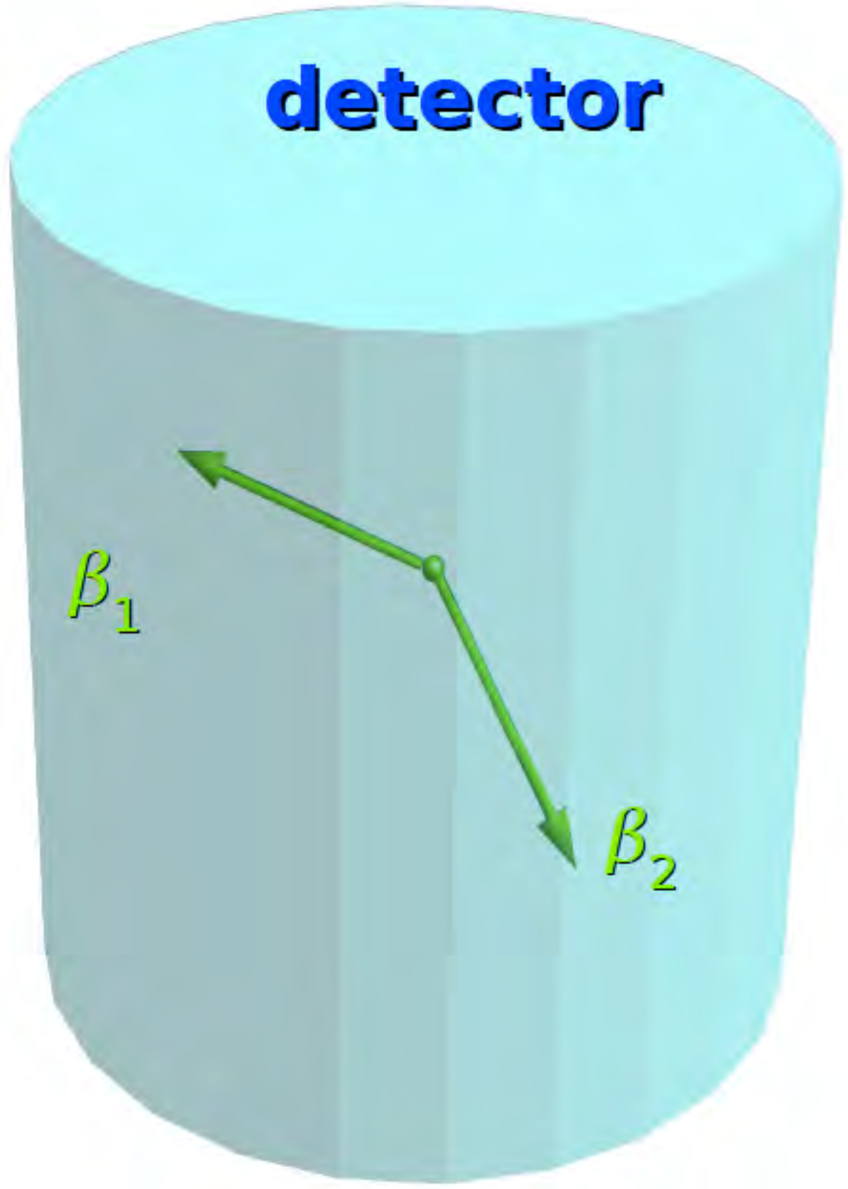
- homogeneous (source ≡ detector) ➞ calorimeters
- inhomogeneous (source ≠ detector) ➞ trackers

… and mixed solutions

Experimental approaches

Two main approaches:

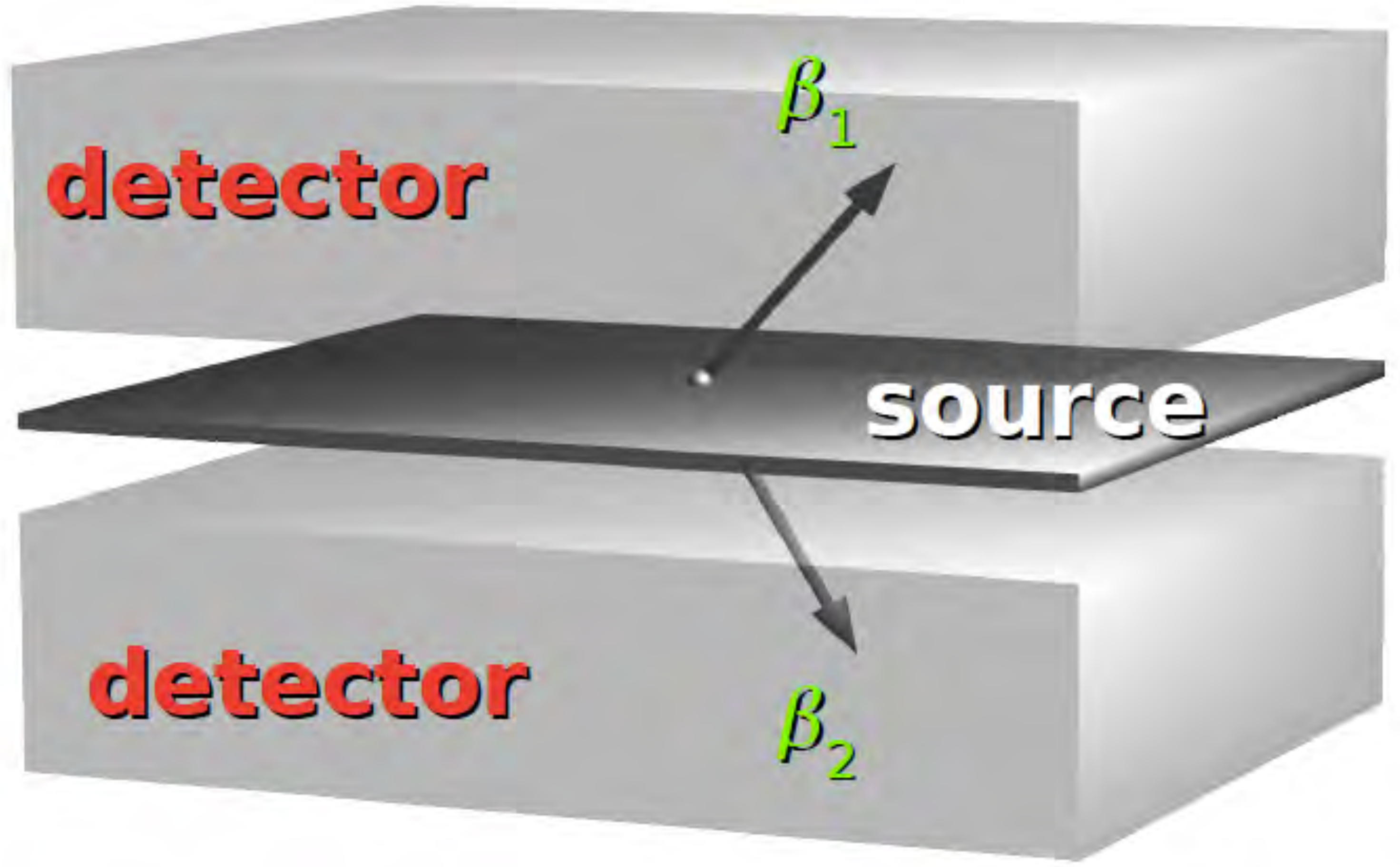
- homogeneous (calorimetric or active source)
- inhomogeneous (external-source or passive source)



Calorimeters

Solid-state devices, bolometers, scintillators, gas detectors

+ Very large M possible (~10kg ➝ tons)
+ High efficiency (ε~1)
+ Very high energy resolution (ΔE~0.15% with Ge-diodes, bolometers)
+ Event topology (in gas/liquid Xe detectors or pixellization)
+ Good background levels
- Constraints on detector material (except for bolometers)
- No or partial particle id



External-source detectors

Scintillators, gas TPC, gas DC, magnetic field and TOF

+ Event topology allowing ¨clean bkg¨ (except 2νββ)
+ Several ββ candidates can be studied with same detector
- Difficult to get large source M
- Difficult to get high efficiency
- Difficult to get good resolution

Experimental sensitivity

$$\tau^{0\nu}_{1/2} = ln2\frac{\epsilon N_{nuclei} t_{meas}}{N_{\beta\beta}}$$

Lifetime corresponding to the minimum detectable number of events over background at a given confidence level

$$N_{\beta\beta} \leq \sqrt{bkg \cdot \Delta E \cdot M \cdot t_{meas}}$$

N_{nuclei}	number of active nuclei in the experiment
t_{meas}	measuring time [y]
M	detector mass [kg]
ε	detector efficiency
i.a.	isotopic abundance
A	atomic number
ΔE	energy resolution [keV]
bkg	background [c/keV/y/kg]

N_B = bkg·ΔE·T·M number of background events expected along the experiment lifetime

$N_B >> 1$

$$S^{0\nu}_{1/2} \propto \epsilon\frac{i.a.}{A}\sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$

$N_B \leq O(1)$ → "zero background"

$$S^{0\nu}_{1/2} \propto \epsilon\frac{i.a.}{A} M \cdot t_{meas}$$

- **Isotopical abundance**
- **Mass**
- **Energy resolution**
- **Background level**

Performance

Scale

$$N_B = S \cdot P \equiv 1$$

$$S_{FB} \sim \sqrt{\frac{S}{P}}$$

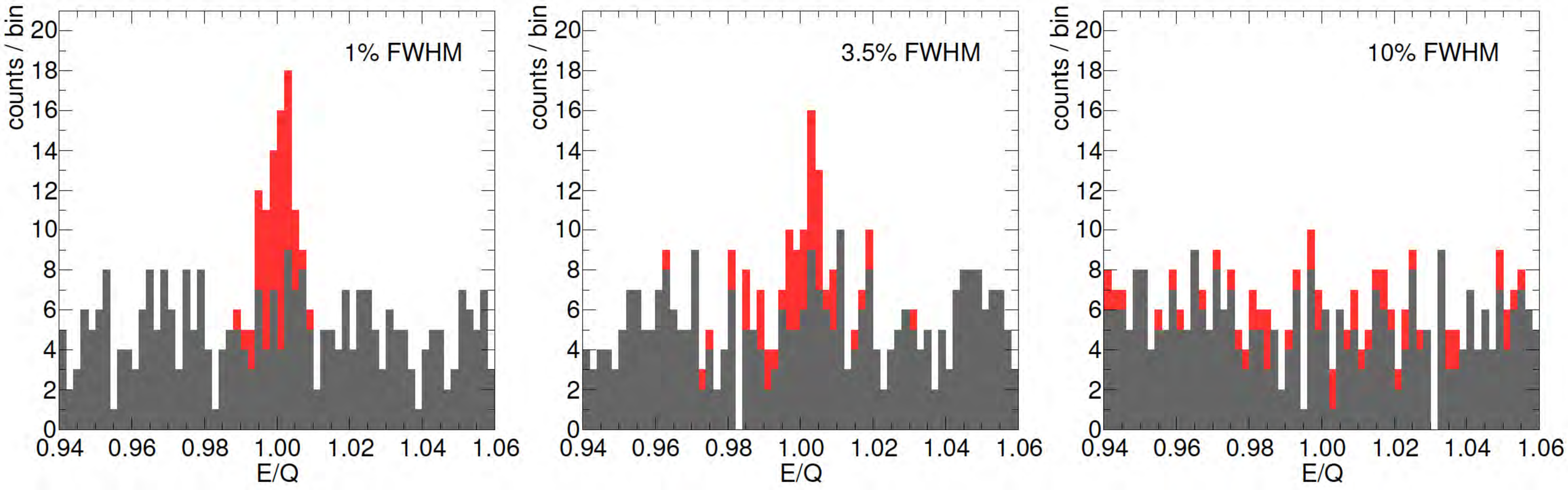
$$S_{ZB} \sim S$$

$< m_{ee} >$

$$\frac{1}{S^{0\nu}_{1/2}(m_{ee})} \propto \sqrt{S^{0\nu}_{1/2} \cdot G^{0\nu}}|M^{0\nu}|$$

- **Isotope choice**

Energy resolution



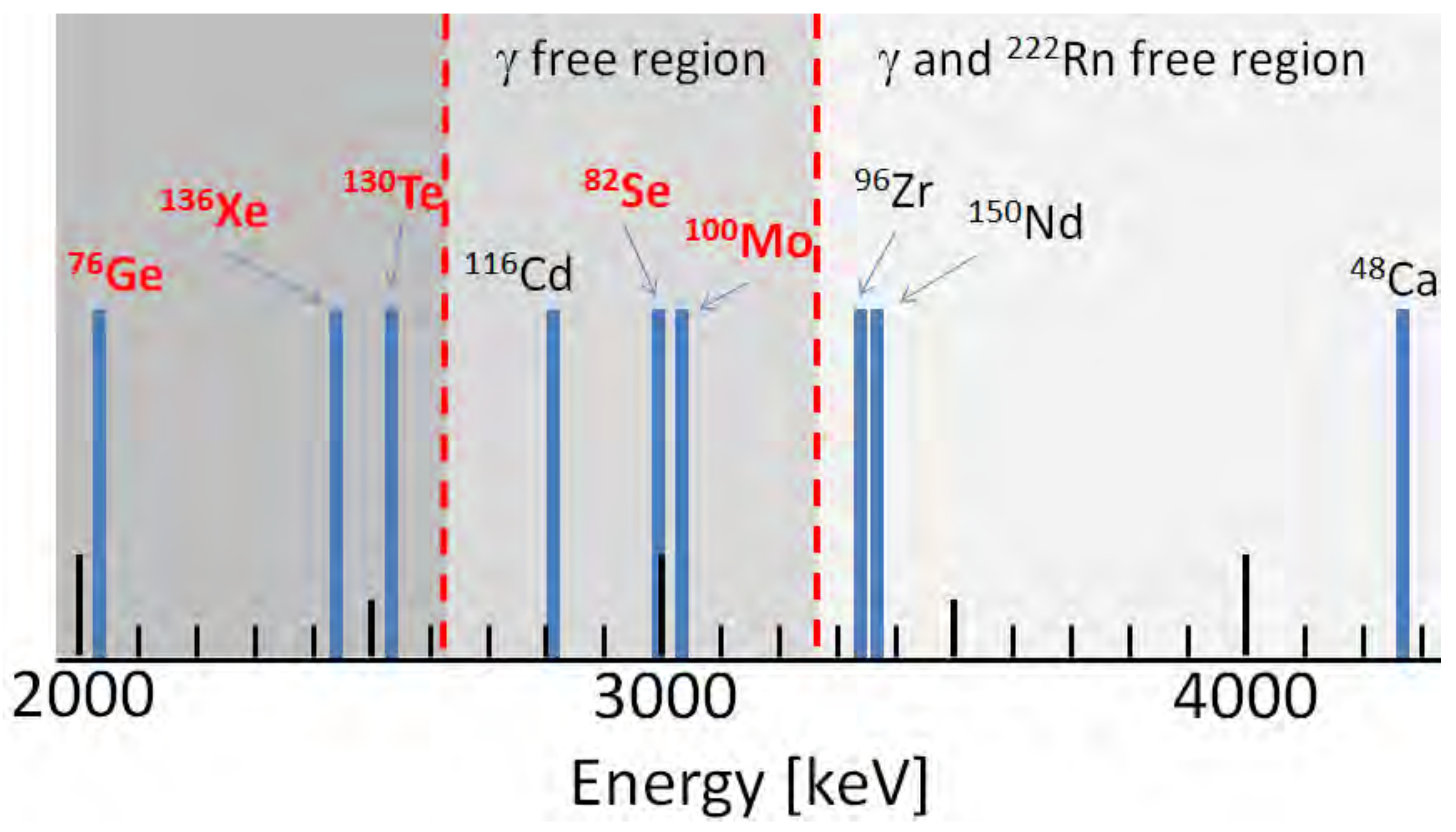
Signal and background (red and grey stacked histograms, respectively) in the region of interest around $Q_{\beta\beta}$ for 3 Monte Carlo experiments with the same signal strength (50 counts) and background rate (1 count keV^{-1}), but different energy resolutions: top: 1% FWHM, centre: 3.5% FWHM, bottom: 10% FWHM. The signal is distributed normally around Q!!, while the background is assumed flat.

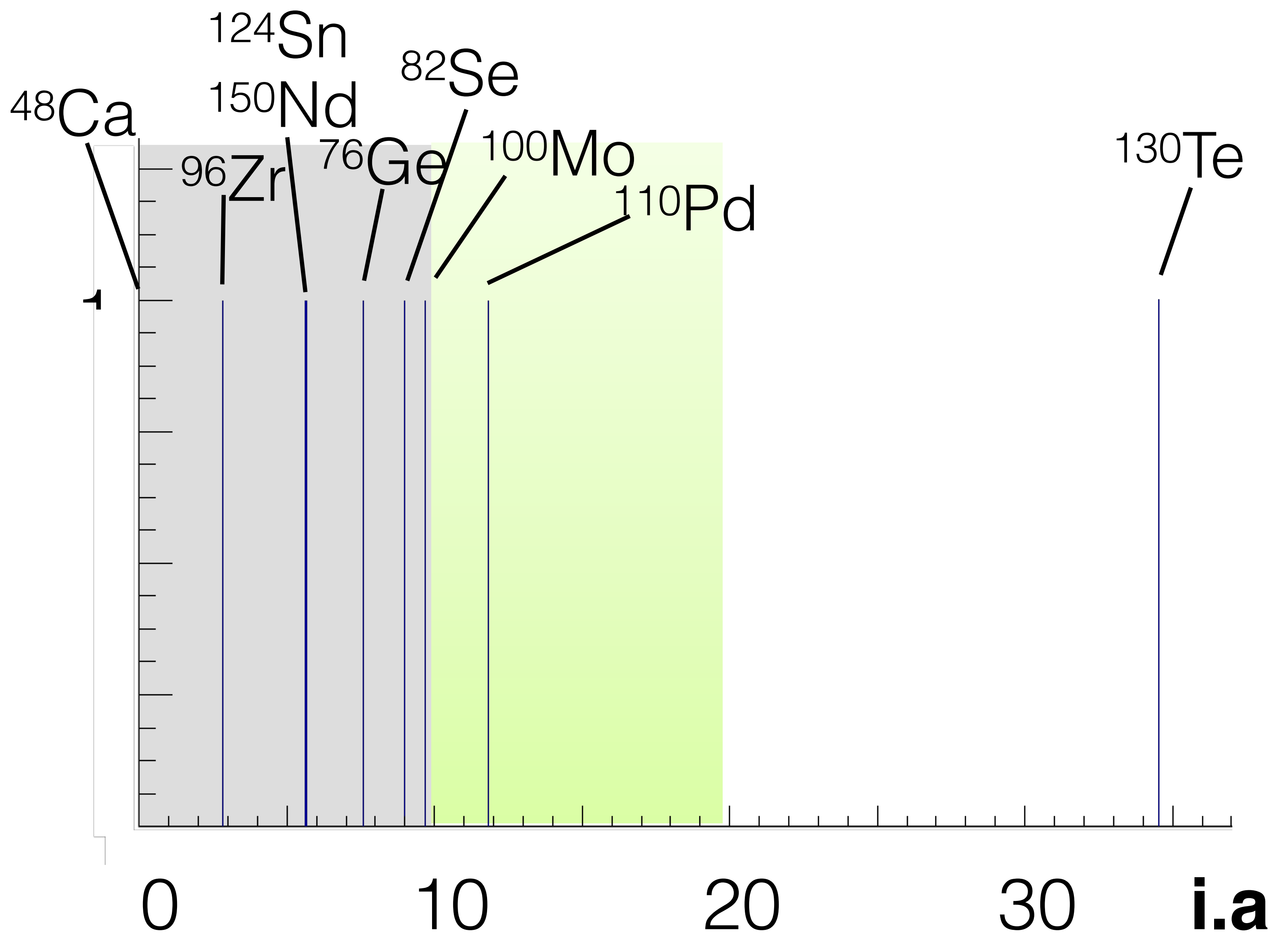
Choice of the isotope

Transition	T0	Abundance	first 2+
	(keV)	(%)	(keV)
46Ca→46Ti	985	0.0035	889
48Ca→48Tit	4272	0.187	984
70Zn→70Ge	1001	0.62	-
76Ge→76Se	2045	7.8	559
80Se→80Kr	136	49.8	-
82Se→82Kr	3005	9.2	776
86Kr→86Sr	1249	17.3	1077
94Zr→94Mo	1148	17.4	871
96Zr→96Mo	3350	2.8	778
98Mr→98Ru	111	24.1	-
1OOMo→1OORu	3033	9.6	540
104Ru→104pd	1301	18.7	556
110Pd→110Cd	2014	11.8	658
114Cd→114Sn	540	28.7	-
116Cd→116Sn	2808	7.5	1294
122Sn→122Te	358	4.56	-
124Sn→124Te	2278	5.64	603
128Te→128Xe	869	31.7	443
130Te→130Xe	2533	34.5	536

Transition	T0	Abundance	first 2+
	(keV)	(%)	(keV)
134Xe→134Ba	843	10.4.	605
136Xe→136Ba	2481	8.9	819
142Ce→142Nd	1414	11.1	-
146Nd→146Sm	61	17.2	-
148Nd→148Sm	1928	5.7	550
150Nd→150Sm	3367	5.6	334
154Sm→154Gd	1250	22.6	123
160Gd→16oDy	1731	21.8	87
170Er→110Yb	655	14.9	84
176Yb→176Hf	1077	12.6	88
186W→186Os	489	28.6	137
192Os→192Pt	408	41.0	317
198Pt→198Hg	1043	7.2	412
204Hg→204Pb	414	6.9	-
232Th→232U	850	100	48
232U→232Pu	1146	99.275	44

Transition energy

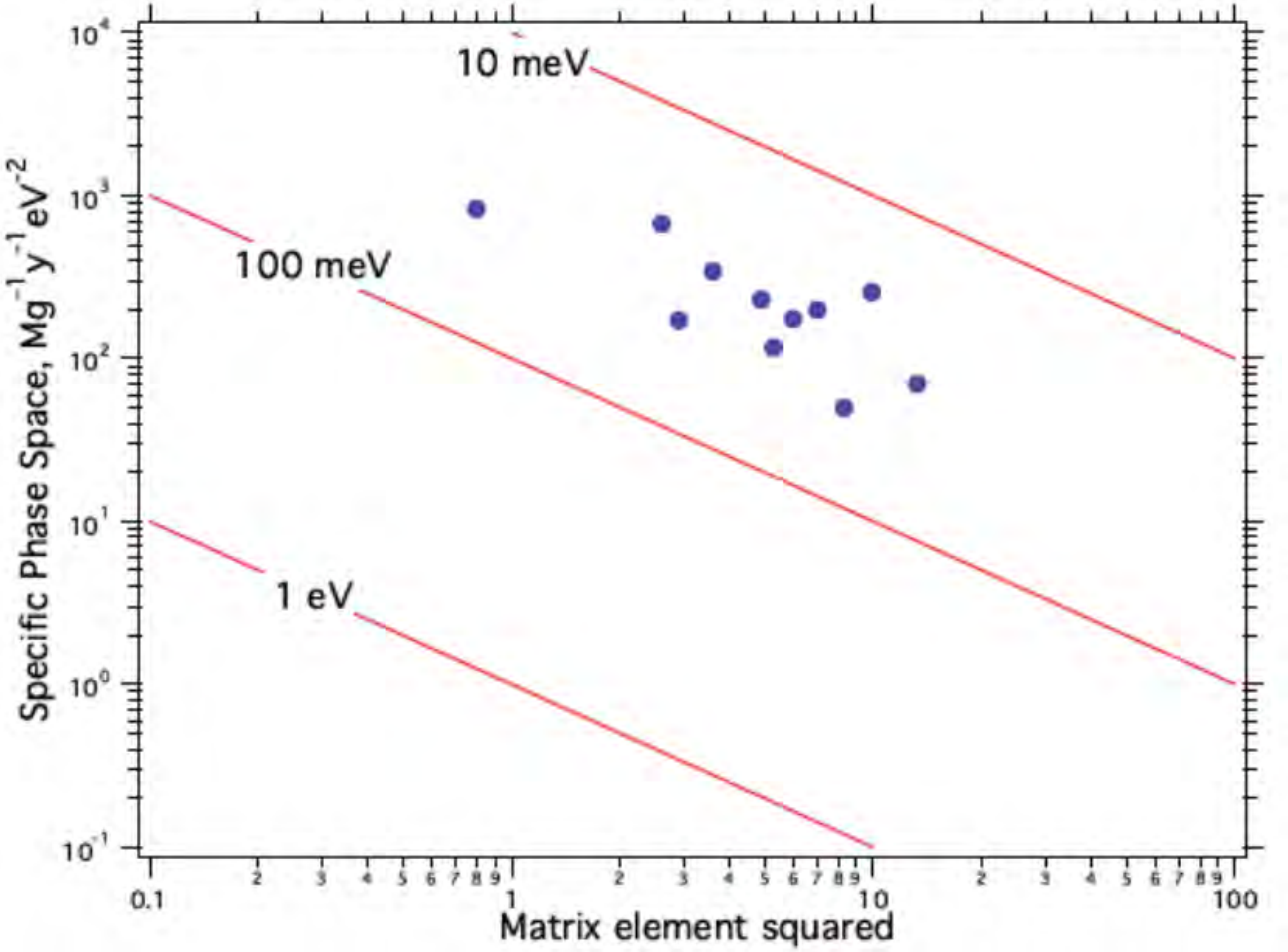




Nucleus choice: golden isotope?

Surprising inverse correlation observed between phase space and the square of the nuclear matrix element

uncertainty on NME



If this holds:
conclusions about τ sensitivity translate directly (within a non negligible uncertainty range) on m_{ee} sensitivity

uncertainty on g_A

geometric mean of the squared matrix element range limits & the phase-space factor evaluated at g_A=1

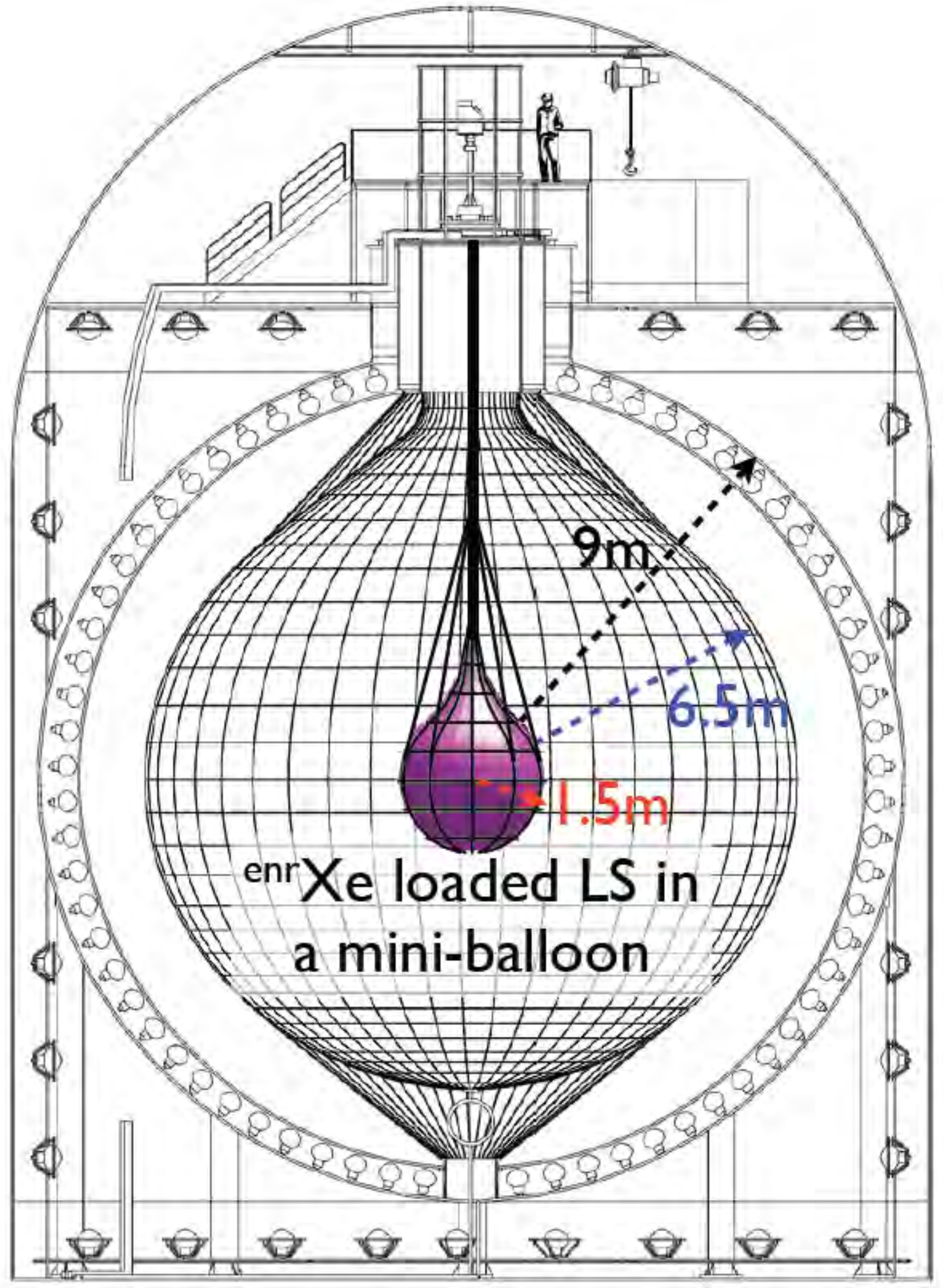
DBD experiments summary

Experiment	Isotope	m_{fid}(ßß) [kg]	Technique	Laboratory	Status
CANDLES	48Ca	305	CaF2 crystals - liq. scintillator	Kamioka	Construction
CARVEL	48Ca		48CaWO4 crystal scint.		R&D
GERDA I	76Ge	14	Ge diodes in LAr	LNGS	Complete
GERDA II	76Ge	31	Point contact Ge in LAr	LNGS	Operating
Majorana D	76Ge	26	Point contact Ge	SURF	Operating
LEGEND-200	76Ge	172	Point contact Ge in LAr	LNGS	R&D
NEMO3	100Mo/82Se	6.9/0.9	Foils with tracking	LSM	Complete
SuperNEMO D	82Se	6.3	Foils with tracking	LSM	Construction
SuperNEMO	82Se	126	Foils with tracking		R&D
CUPID-0	82Se	5	ZnSe scint. bolometer	LNGS	Operating
AMoRE	100Mo	50	CaMoO4 scint. bolometer	Y2L	R&D
MOON	100Mo	200	Mo sheets		R&D
COBRA	116Cd	10/183	CdZnTe detectors	LNGS	R&D
CUORICINO	130Te	10	TeO2 Bolometer	LNGS	Complete
CUORE-0	130Te	11	TeO2 Bolometer	LNGS	Complete
CUORE	130Te	206	TeO2 Bolometer	LNGS	Operating
SNO+	130Te	55	0.1% natNd suspended in Scint	SNOlab	Commissioning
KamLAND-ZEN	136Xe	380	2.7% in liquid scint.	Kamioka	Operating
NEXT-100	136Xe	90	High pressure Xe TPC	LSC	Construction
EXO-200	136Xe	60	Xe liquid TPC	WIPP	Operating
nEXO	136Xe	450/3330	Xe liquid TPC	SNOlab	R&D
PandaX-III	136Xe	200	High pressure Xe TPC	CJPL-II	R&D
DCBA	150Nd		Nd foils & tracking chambers		R&D

- WIPP in USA (EXO-200)
- LSM in France (CUPID-Mo)
- Kamioka in Japan (XMASS,KamLAND-Zen)
- Y2L in Corea (Amore)
- LSC in Spain (NEXT,SuperNEMO-D)
- LNGS in Italy (CUORE,GERDA,CUPID-Se)
- SURF in USA (MJD)
- SNOLAB in Canada (SNO+)
- Jin-Ping in China (CUPID-China)

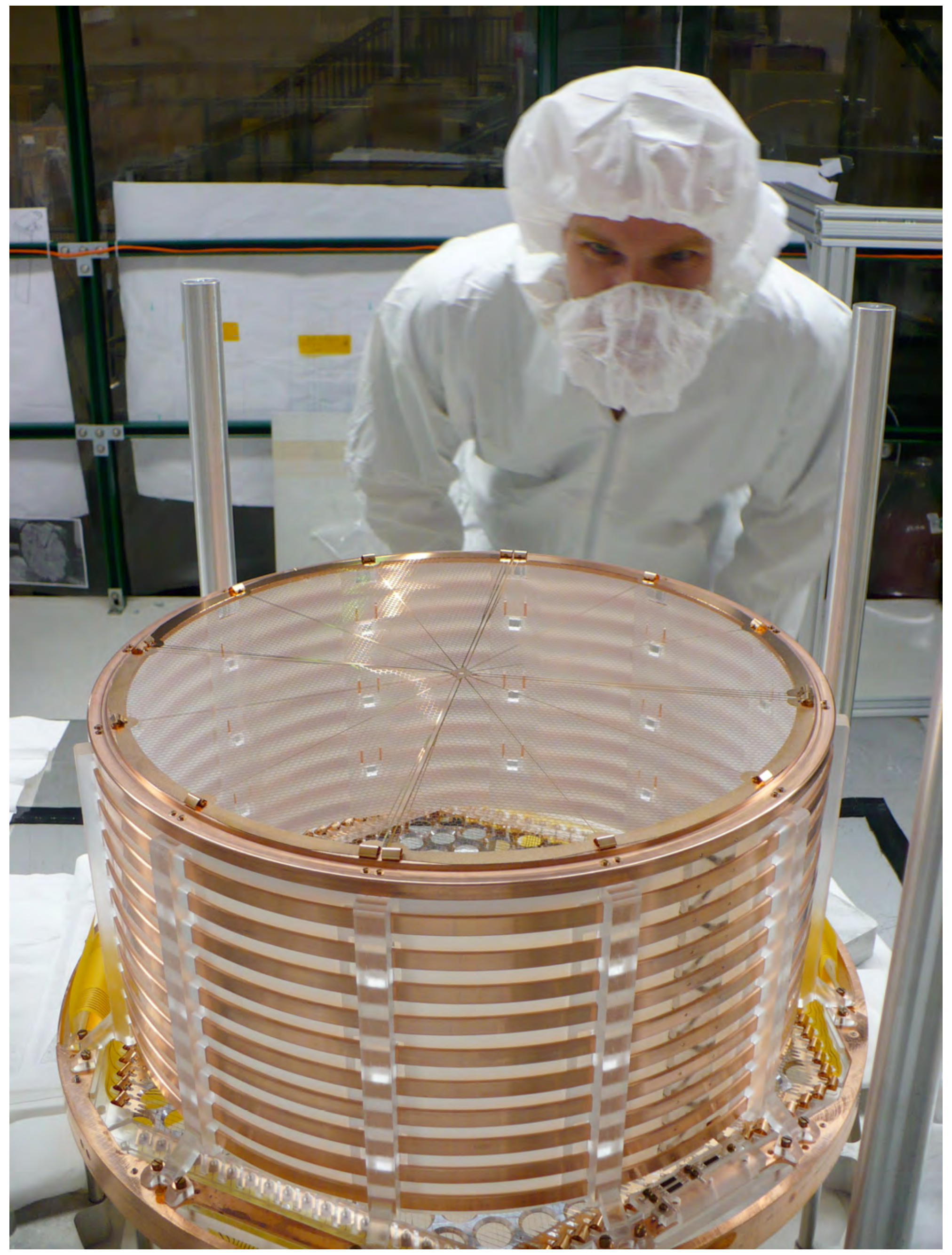
Present

GERDA-II



KamLAND-ZEN

EXO-200



MAJORANA DEM.

CUORE

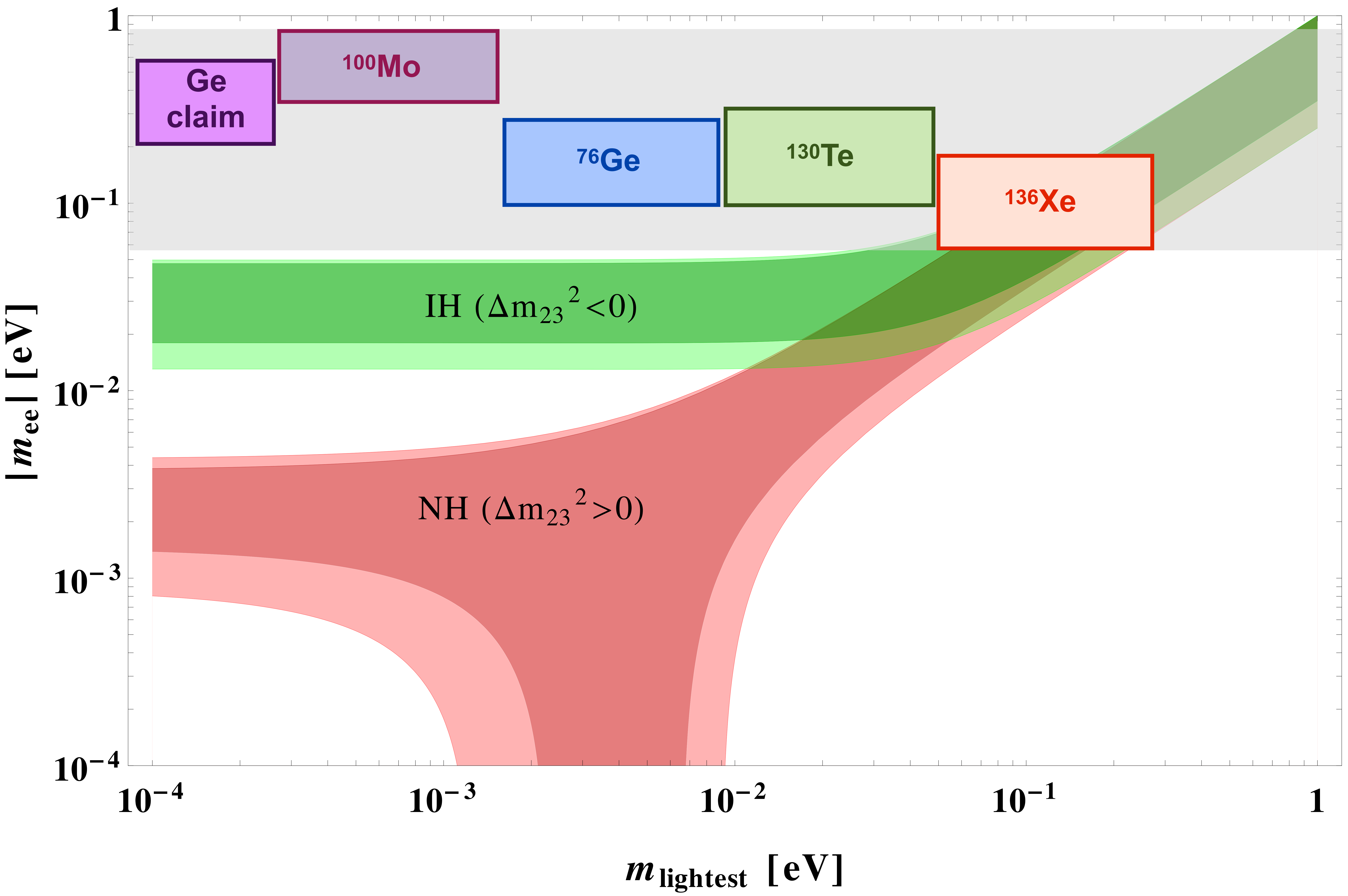
An exciting moment

- Current experiments are characterised by sensitivities O(10^{26} yr) on the half lifetime
- Depending on the evolution of the discussion on NME's and g_A quenching they will approach or enter the IH band of neutrino masses
- Most of them are developments of previous experiments (or demonstrators)

Status

no gA quenching assumed

Present results



Latest results (March 2018)

Experiment	Isotope	Limit $T_{1/2}$ (yr)	Median Sensitivity	BI (10^{-3} c/(keV kg yr))	FWHM (keV)	Exposure (kg·yr)	$m_{\beta\beta}$ (meV)	
GERDA-(I+II)	^{76}Ge	8.00E+25	5.80E+25	$1.0^{+0.6}_{-0.4}$	3.65	23.5+23.2	120-260	Agostini M et al, PRL 120 132503 (2018)
MJD	^{76}Ge	1.90E+25	2.10E+25	$1.6^{+1.2}_{-1.0}$	2.5	9.5	240-520	Aalseth C E et al, PRL 120 132502 (2018)
CUORE	^{130}Te	1.30E+25	7.00E+24	14±2*	7.7	24	110-520	Alduino C et al, PRL 120 132501 (2018)
CUPID-0	^{82}Se	2.40E+24	2.30E+24	$3.6^{+1.9}_{-1.4}$	23	1.83	376-770	Azzolini O et al, PRL 120, 232502 (2018)
EXO-200	^{136}Xe	1.80E+25	3.70E+25	1.5±0.3*	71	177	147-398	Albert J B et al, PRL 120 072701 (2018)
KamLAND-ZEN	^{136}Xe	1.11E+26		0.54±0.09	270	504	61-165	Gando A et al, PRL 117 082503 (2016)

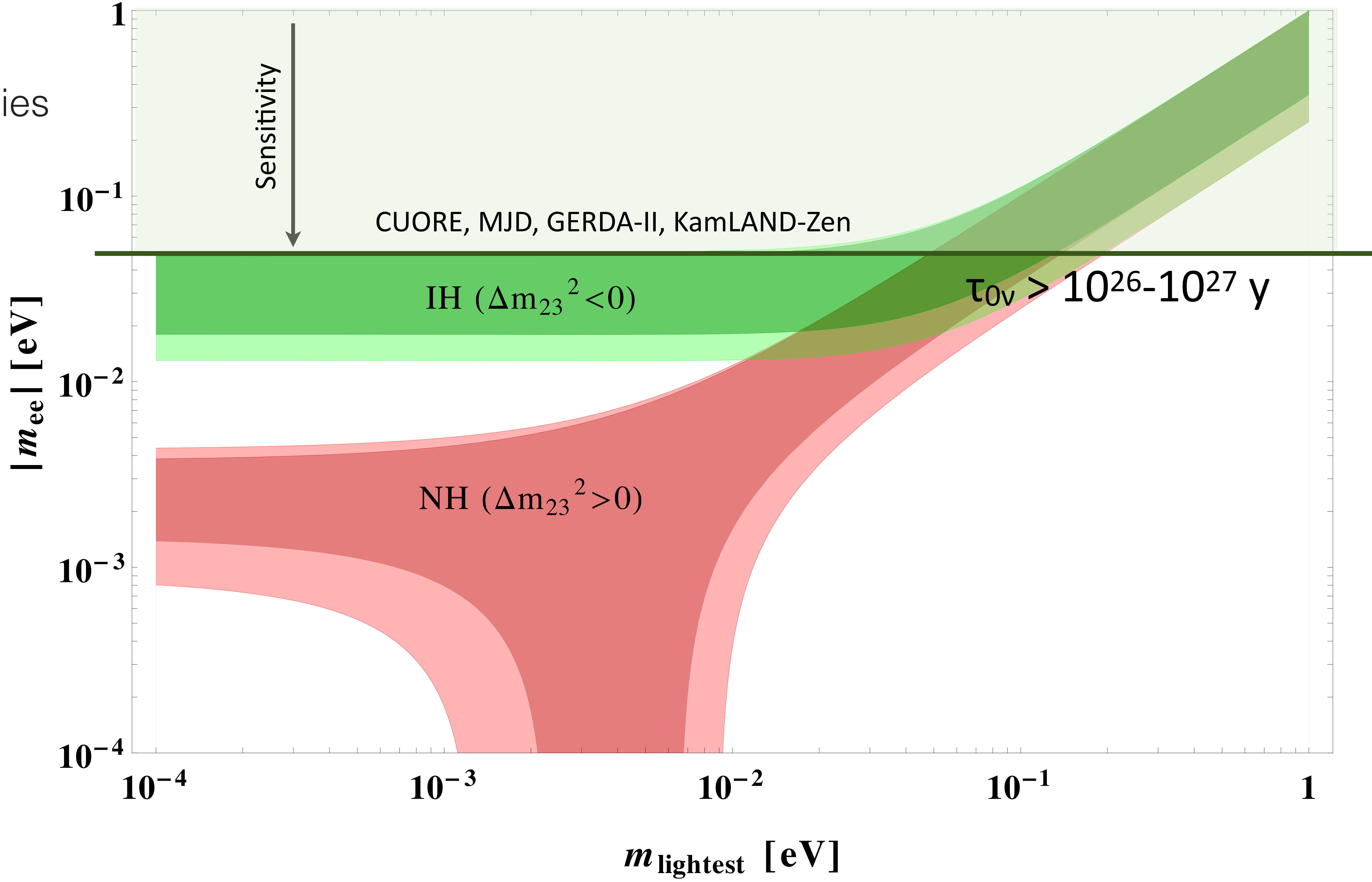
Latest update (Neutrino 2018)

Experiment	Isotope	Limit $T_{1/2}$ (yr)	Median Sensitivity	BI (10^{-3} c/(keV kg yr))	FWHM (keV)	Exposure (kg·yr)	$m_{\beta\beta}$ (meV)	
GERDA-(I+II)	^{76}Ge	9.00E+25	8.0E+25	0.56	3.6/3.0	82.4	120-260	AJ Zsigmond - Neutrino 2018
MJD	^{76}Ge	2.70E+25	4.8E+25	4.7±0.8	2.5	21.3	200-433	VE Giuseppe - Neutrino 2018
CUORE	^{130}Te	1.30E+25	7.00E+24	14±2*	7.7	24	110-520	Alduino C et al, PRL 120 132501 (2018)
CUPID-0	^{82}Se	2.40E+24	2.30E+24	$3.6^{+1.9}_{-1.4}$	23	1.83	376-770	Gando A et al, PRL 117 082503 (2016)
EXO-200	^{136}Xe	1.80E+25	3.70E+25	1.5±0.3*	71	177	147-398	Azzolini O et al, PRL (2018)
KamLAND-ZEN	^{136}Xe	1.11E+26		0.54±0.09	270	504	61-165	Albert J B et al, PRL 120 072701 (2018)

Status

no gA quenching assumed

Present Sensitivities

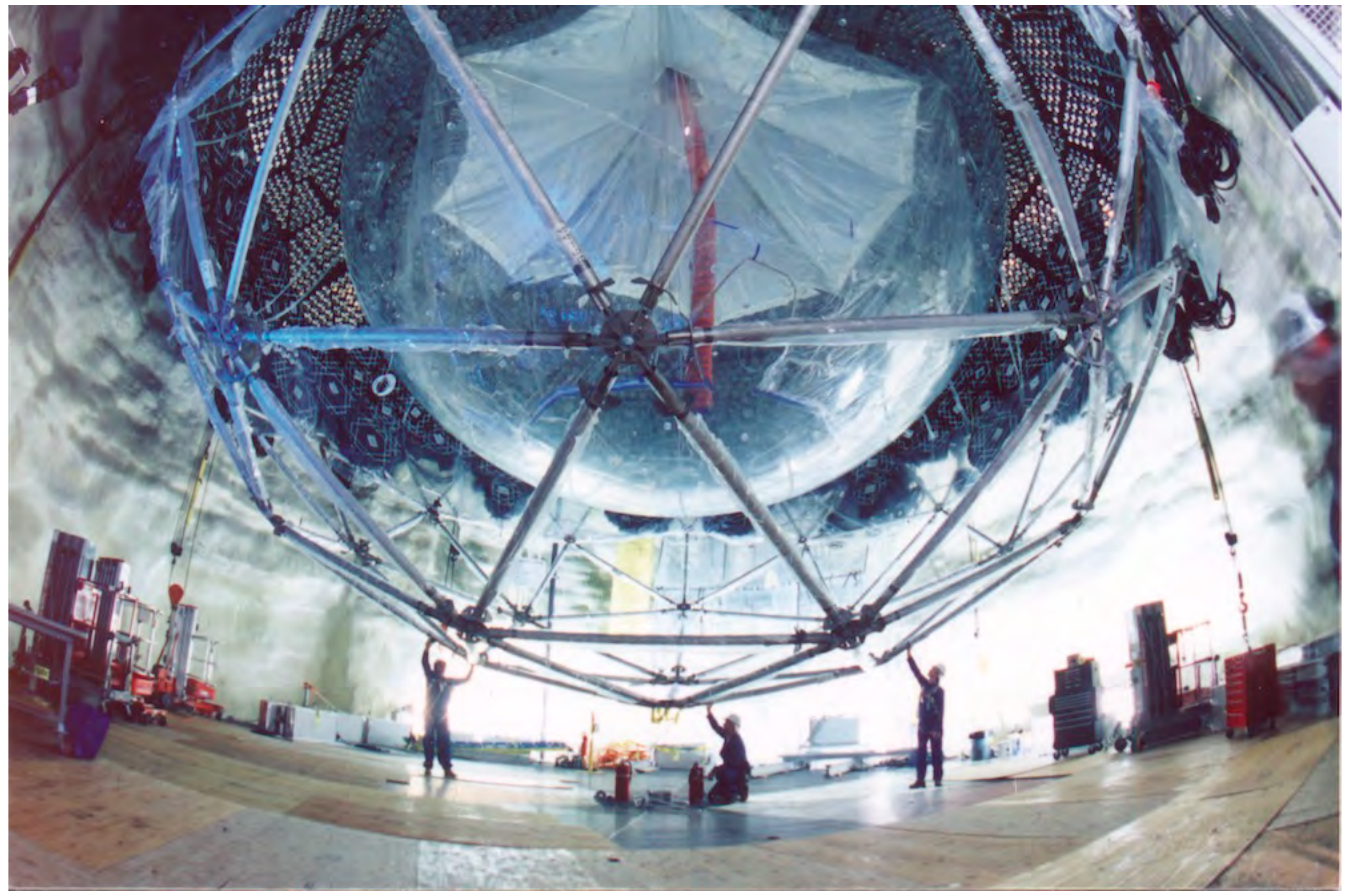


Gazing into a crystal ball

- R&D's to improve sensitivity (performance or scale) have already produced a number of successful results
- Plans for developments aiming at sensitivities $O(10^{27-28}$ yr), i.e. at least one order of magnitude better than present have been already developed and projects proposed
- Next generation experiments will be able to sound the IH region of neutrino masses

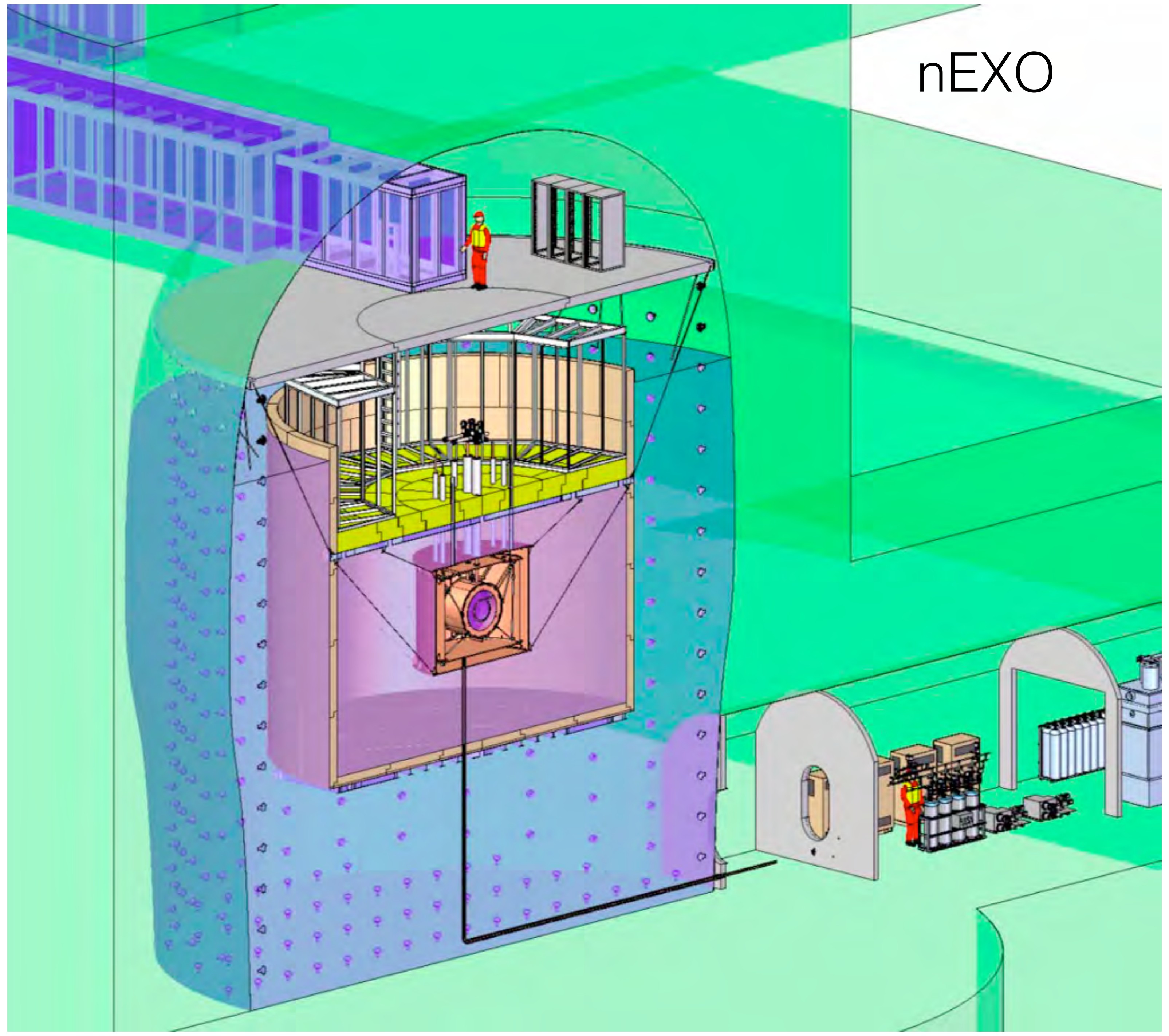
Future

SNO+



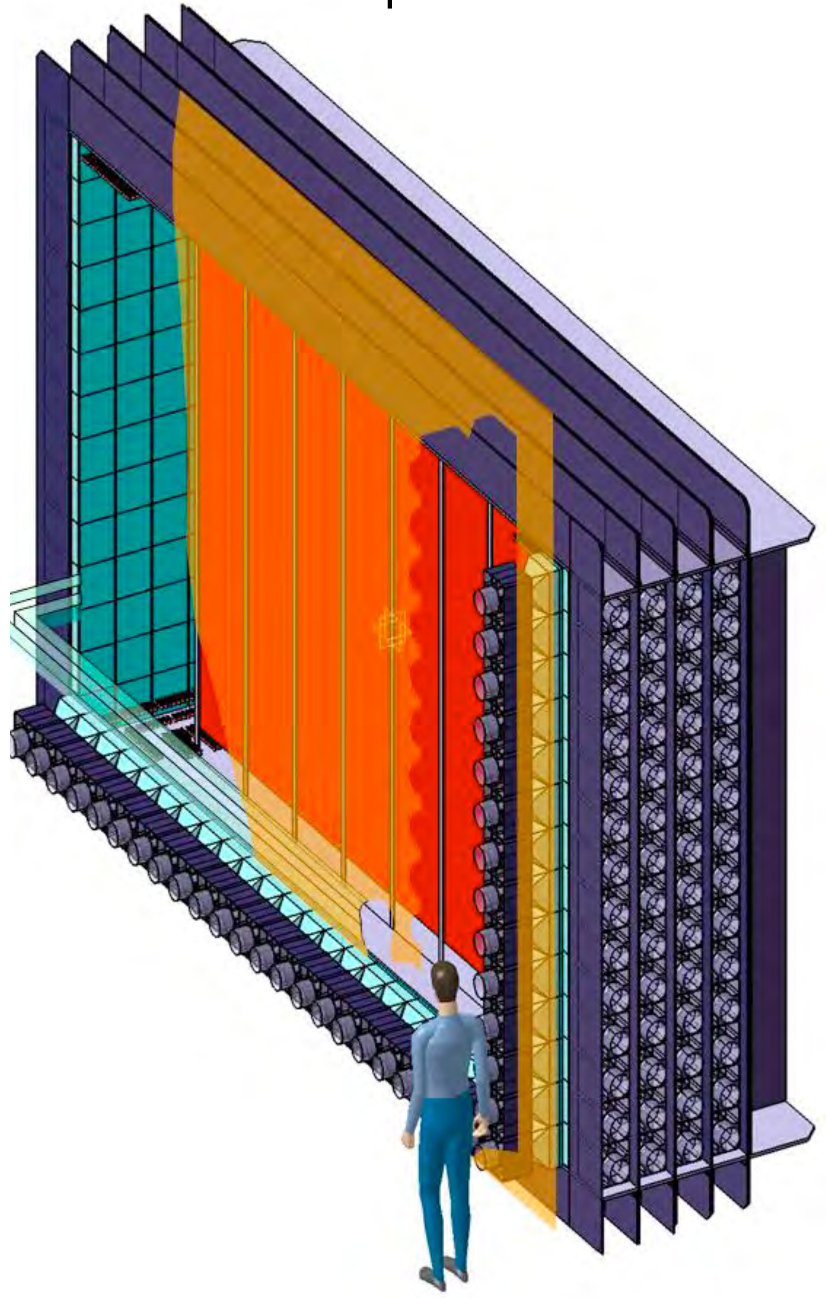
CUPID

nEXO

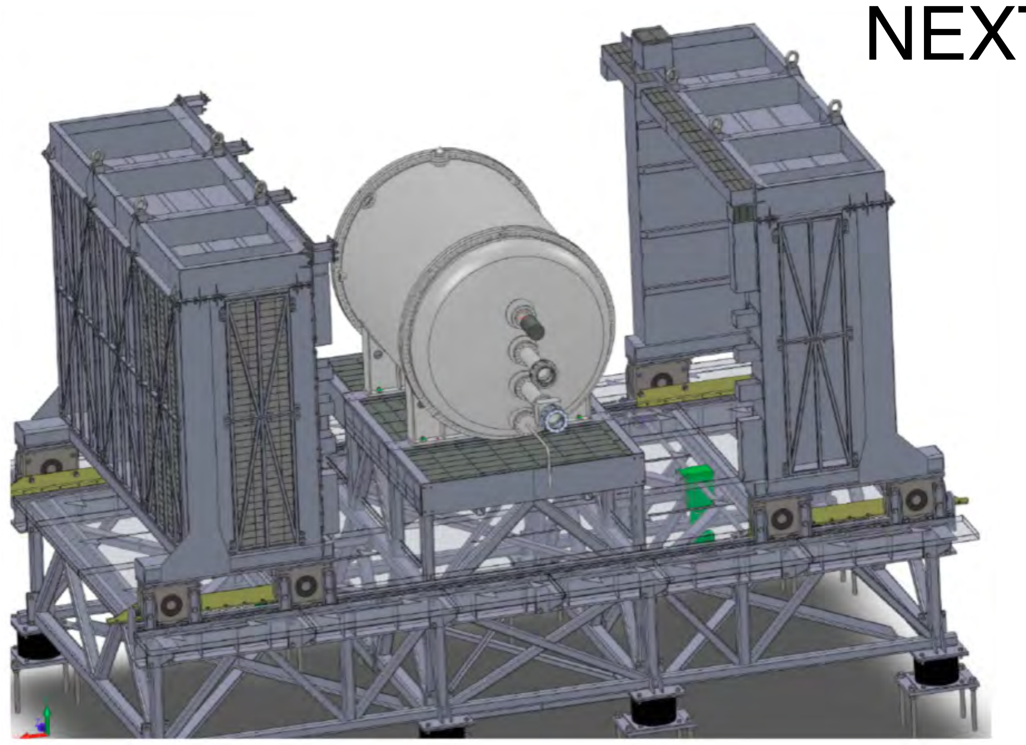


KamLAND-ZEN

SuperNEMO



NEXT

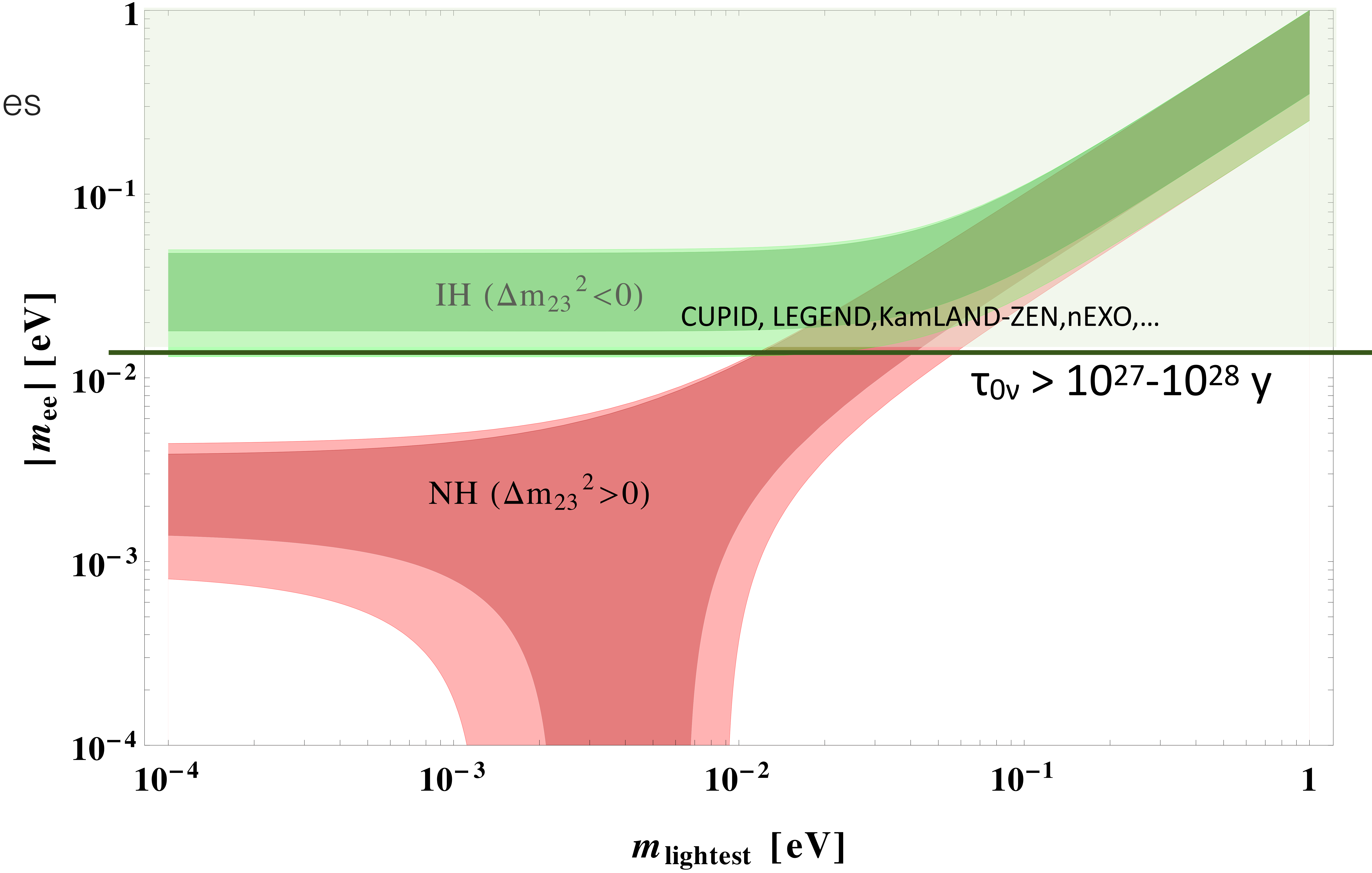


LEGEND

Status

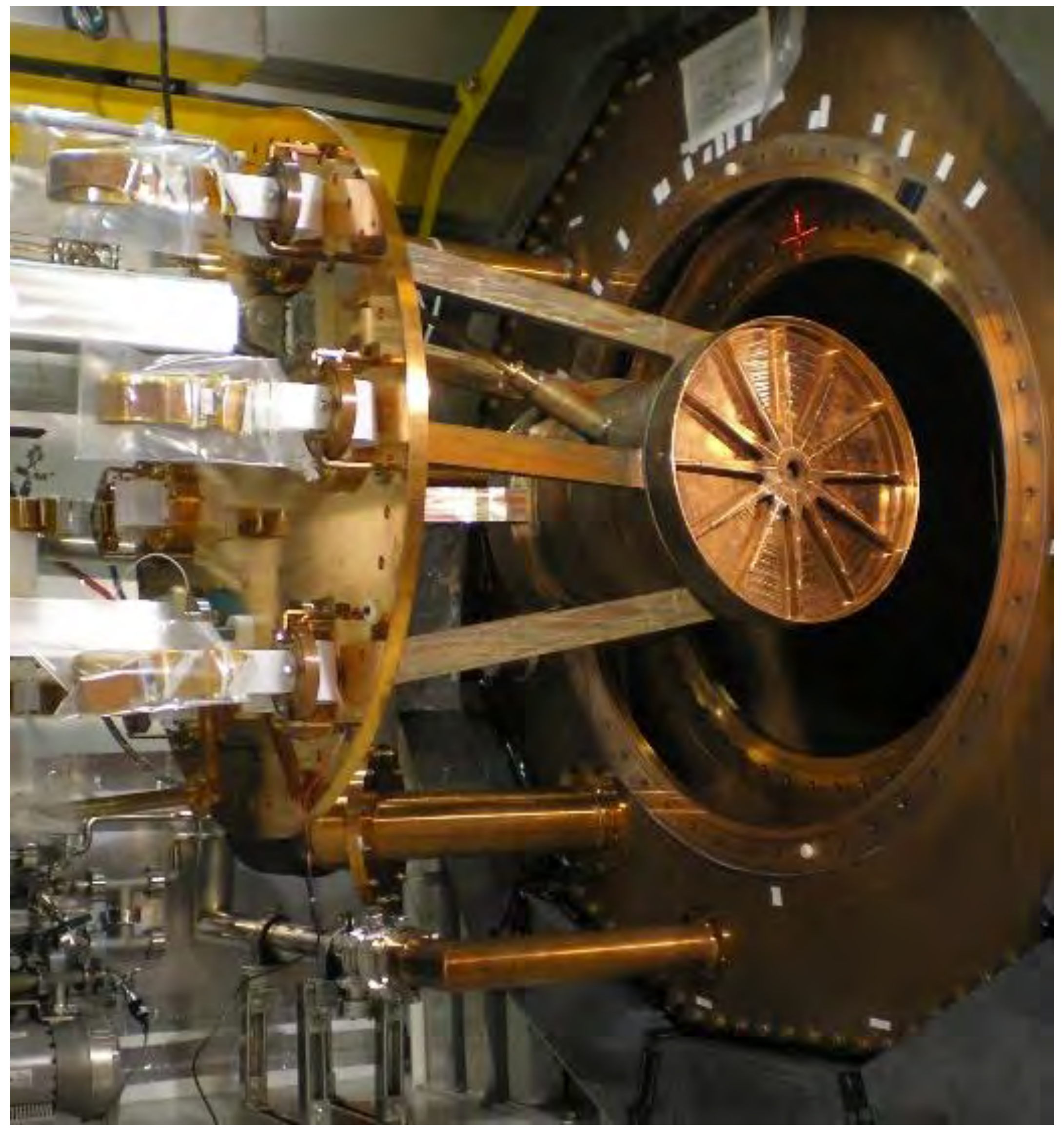
no gA quenching assumed

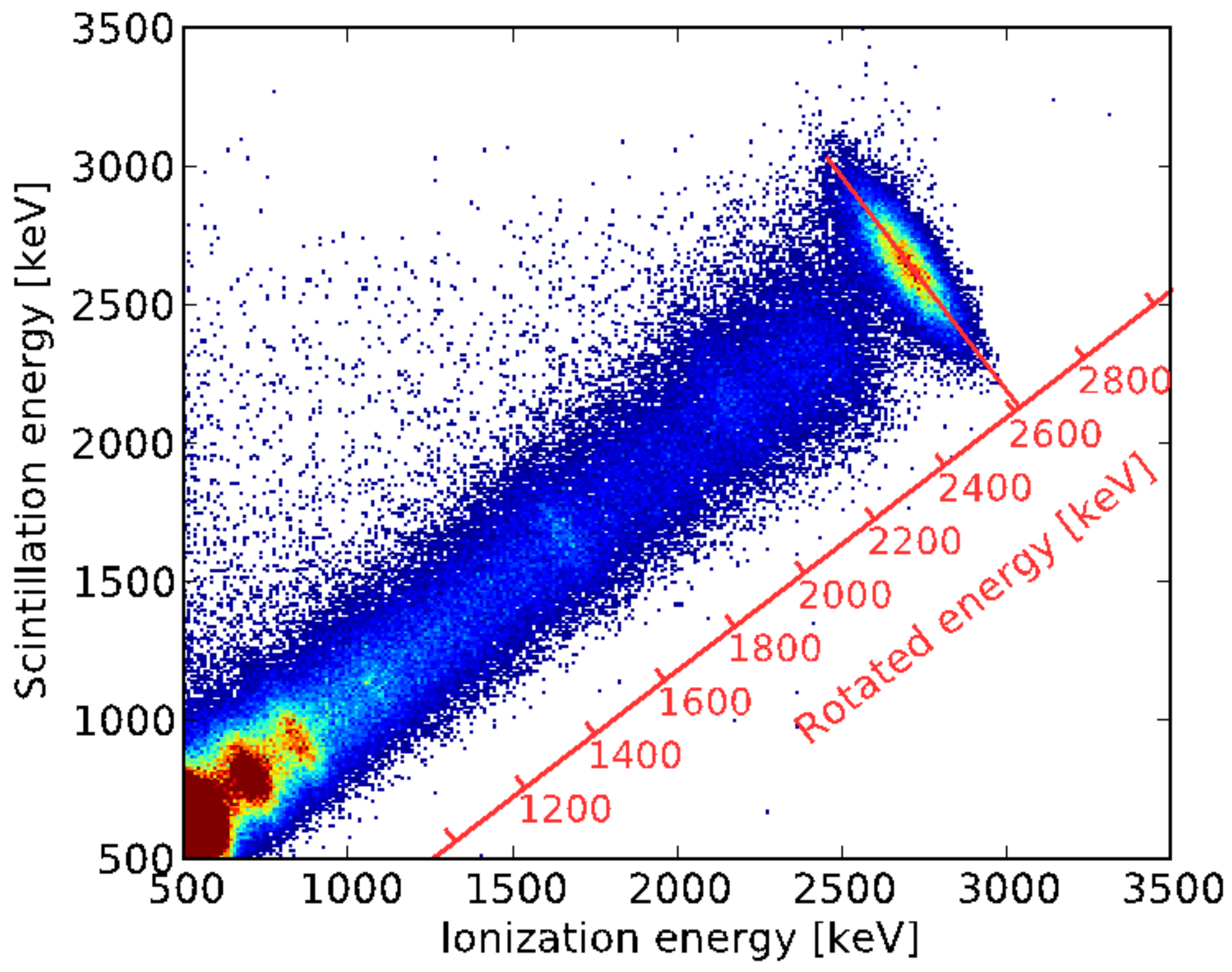
Future Sensitivities

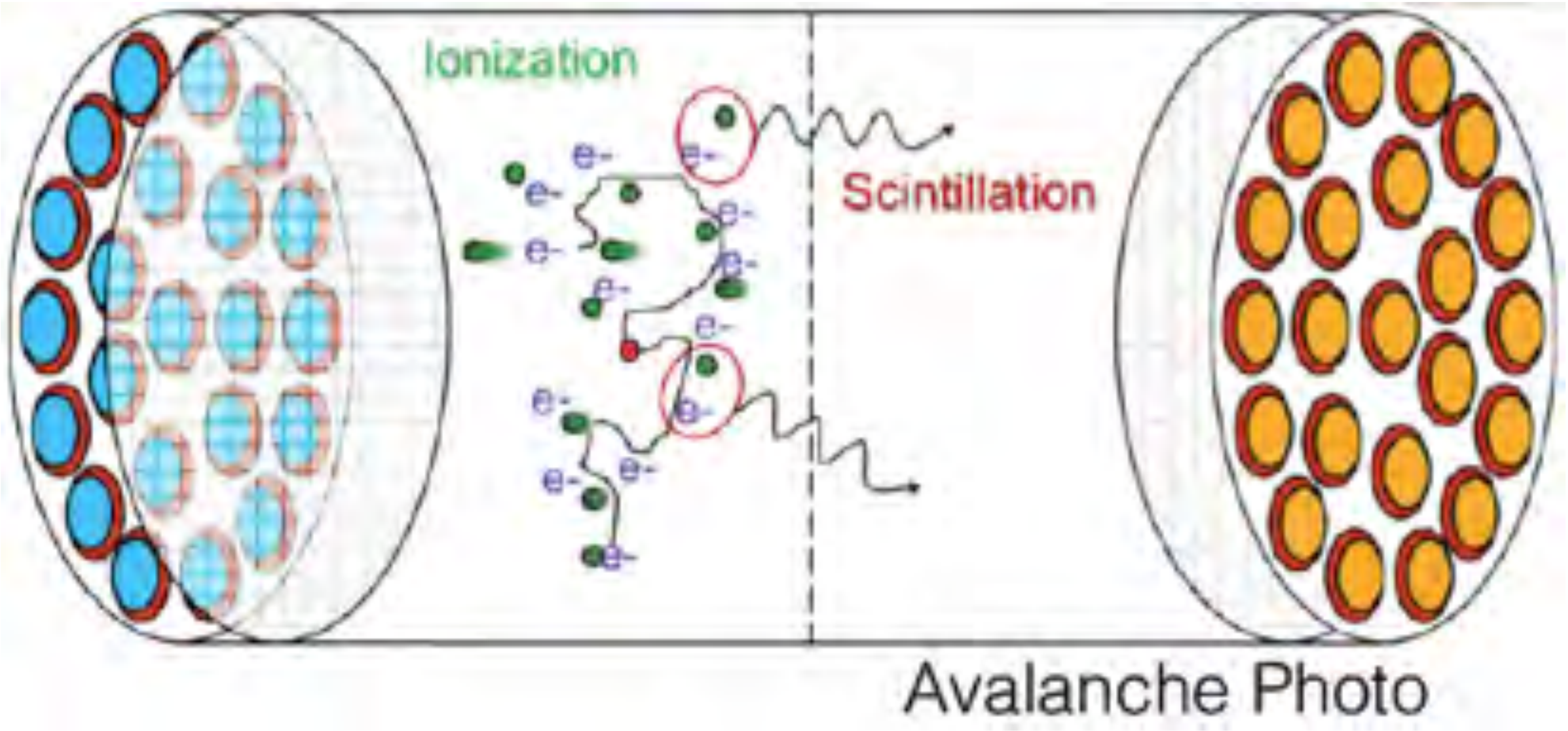


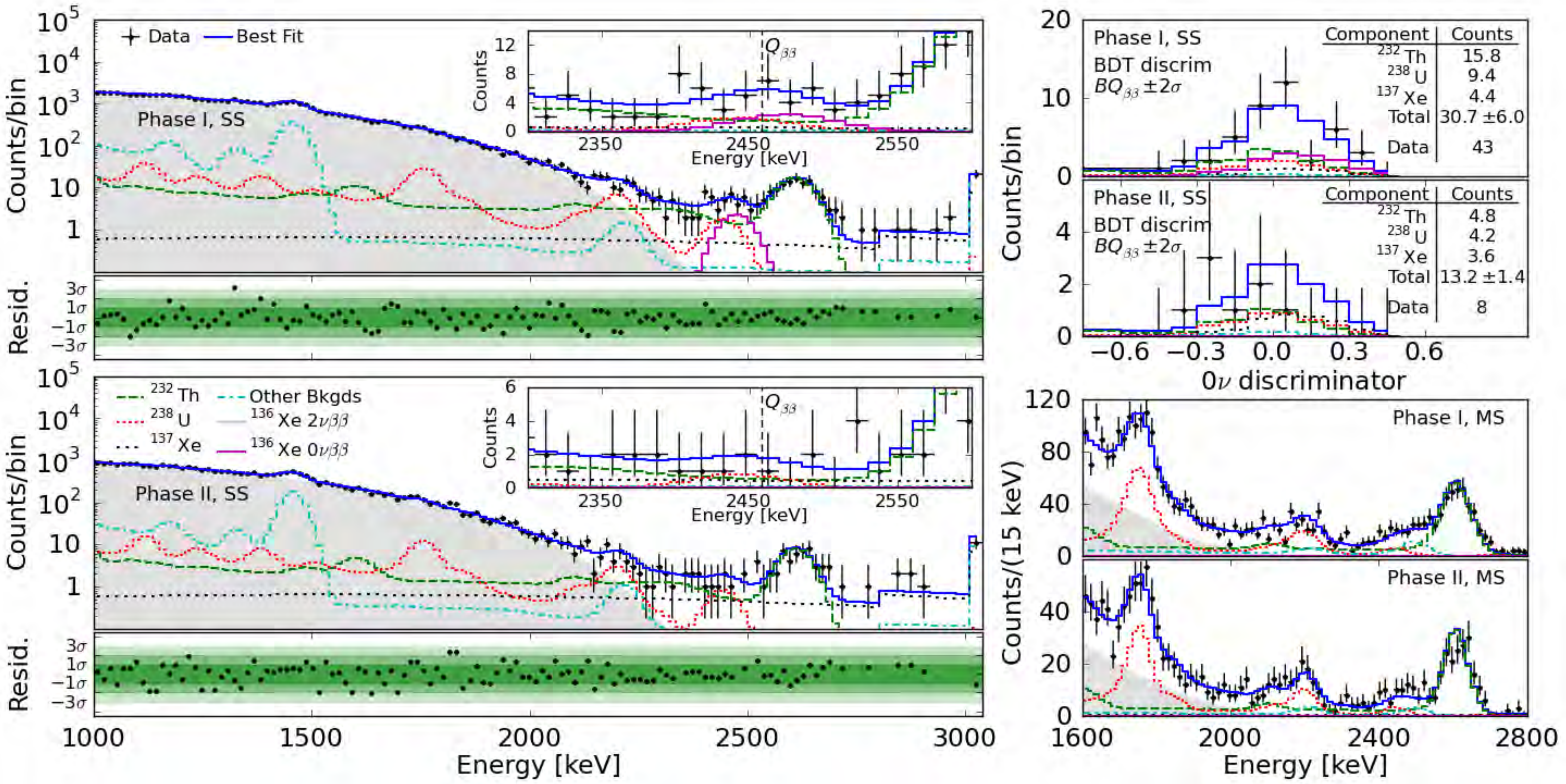
EXO-200

- Liquid Xe TPC (80.6% ^{136}Xe): 75 kg 136Xe in FV
  - Phase I completed: 122 kg·yr (σ/E: 1.6%)
  - Phase II: from Jan 2016 (σ/E: 1.3%)
- Background index: (0.11±0.01) / (kg·yr·FWHM)
- Sensitivity: $3.8 \cdot 10^{25}$
- $T_{1/2} = 1.8 \cdot 10^{25}$yr
- m_{ee}: 147-398 meV

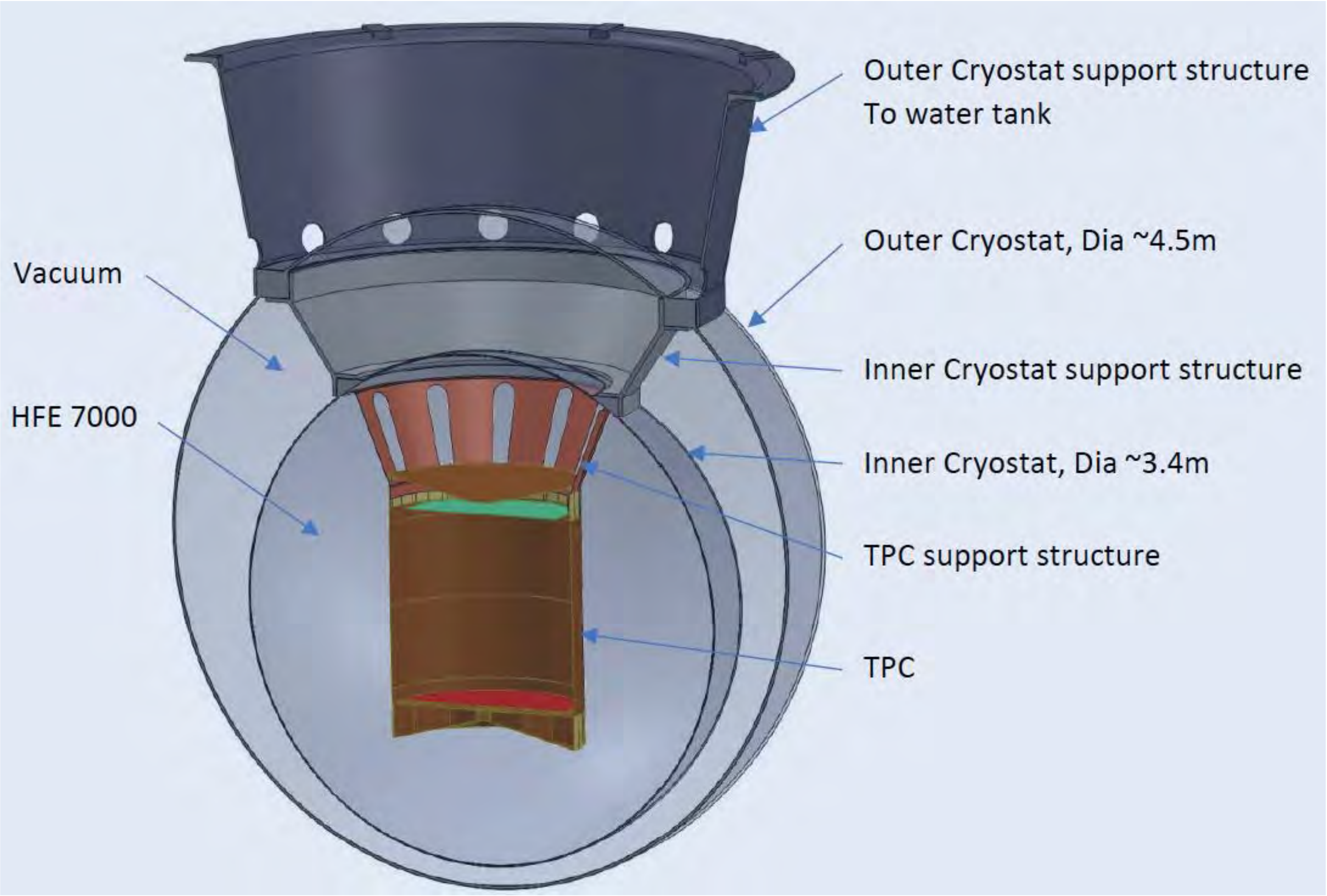


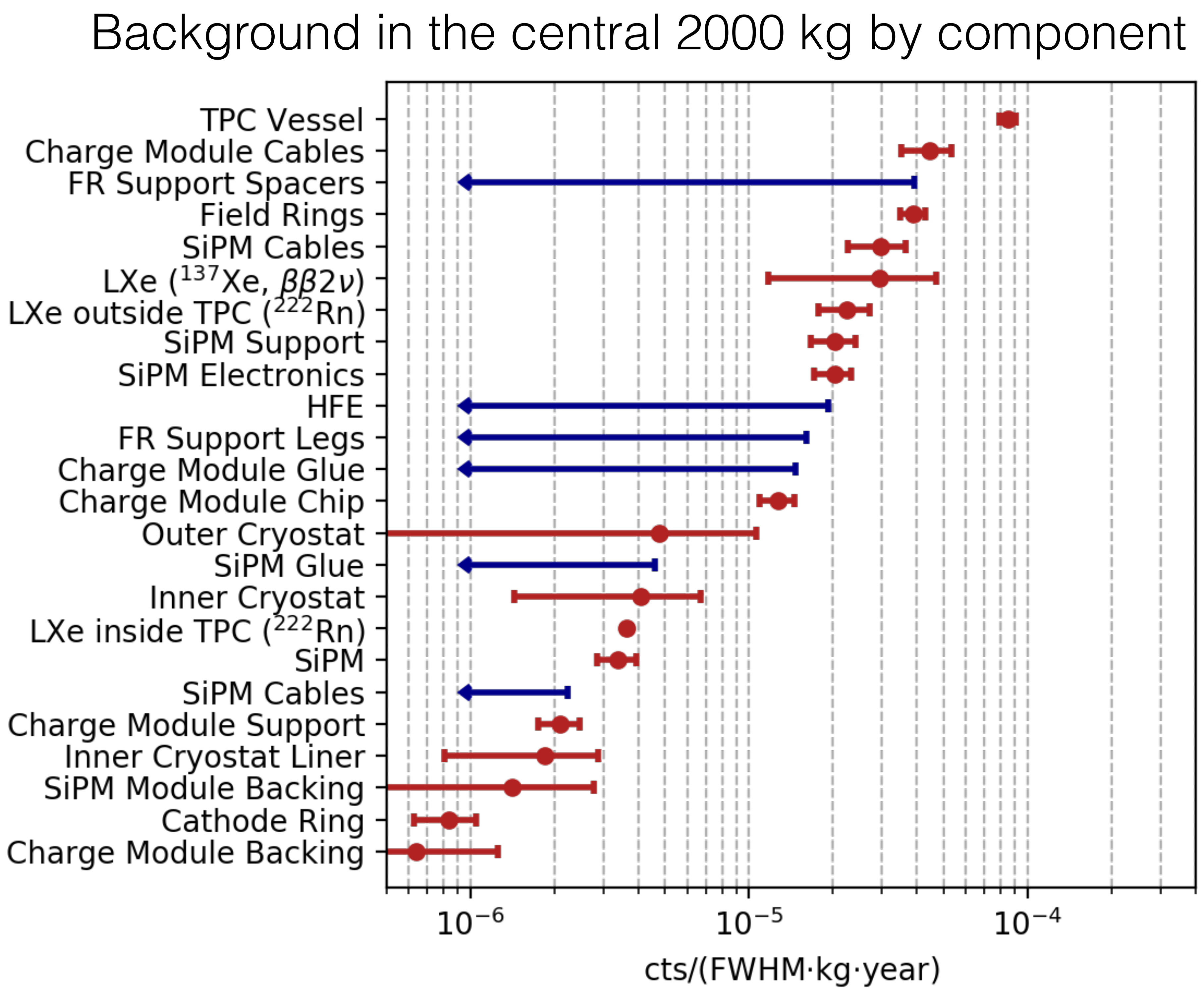


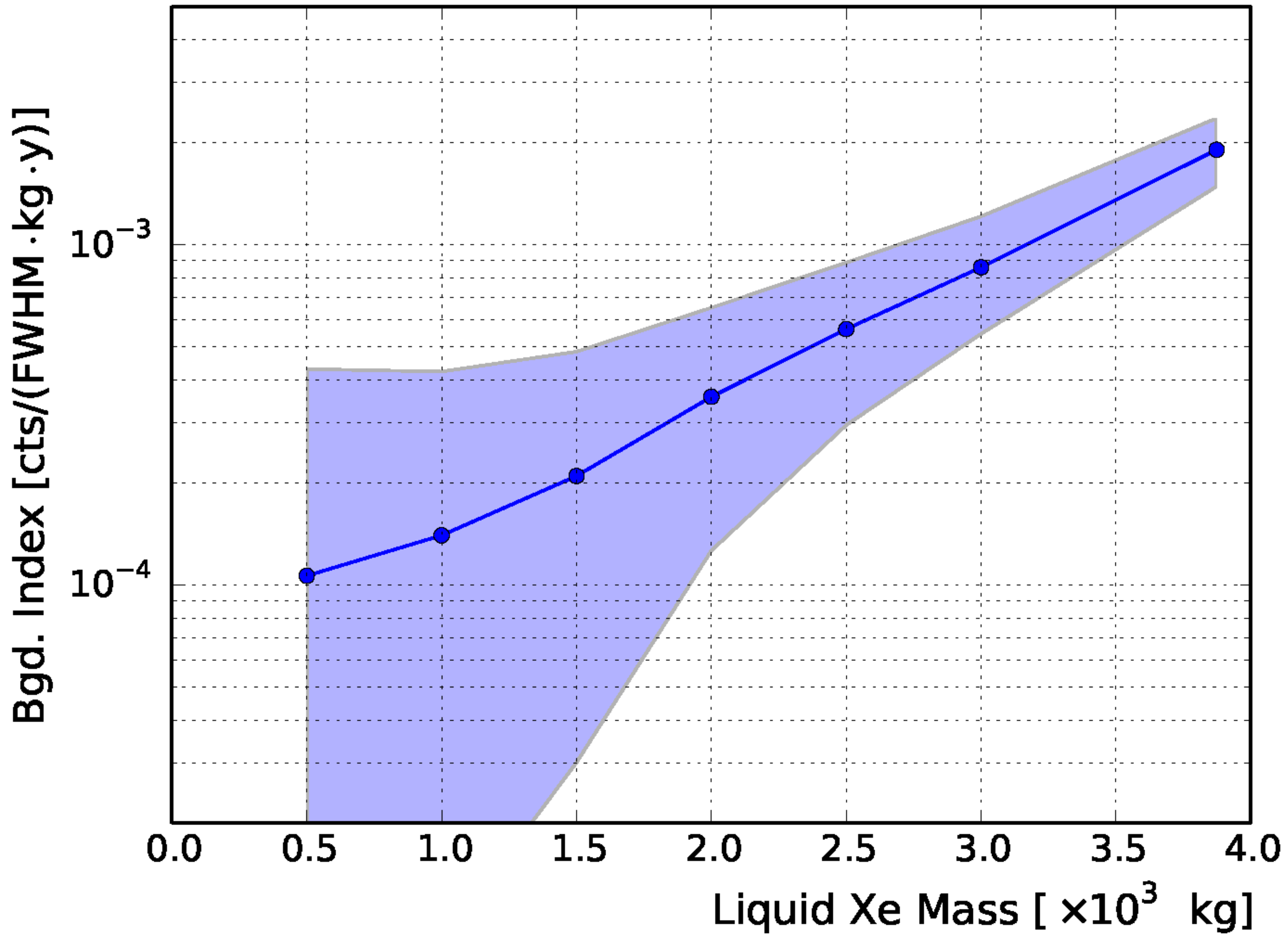




nEXO



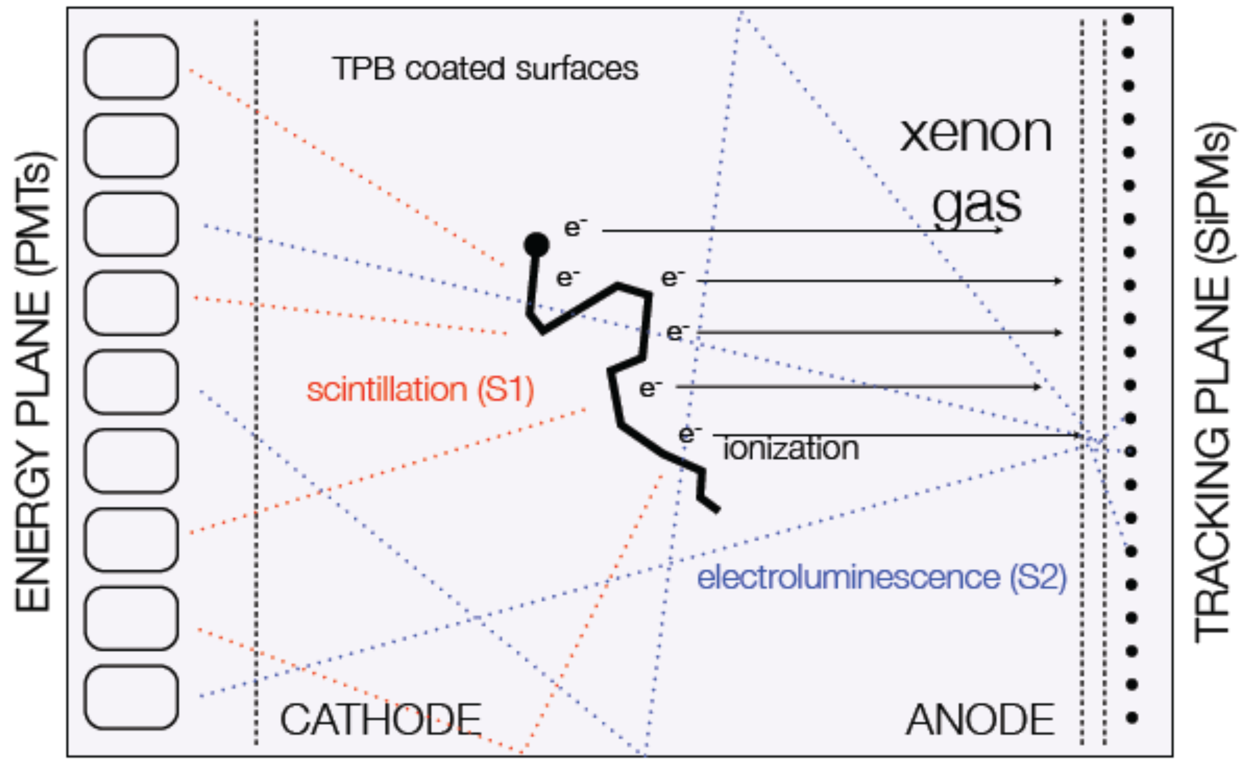




Discovery sensitivity (3σ, 50%) after 10 yr: $T_{1/2} = 5.5 \cdot 10^{27}$ yr

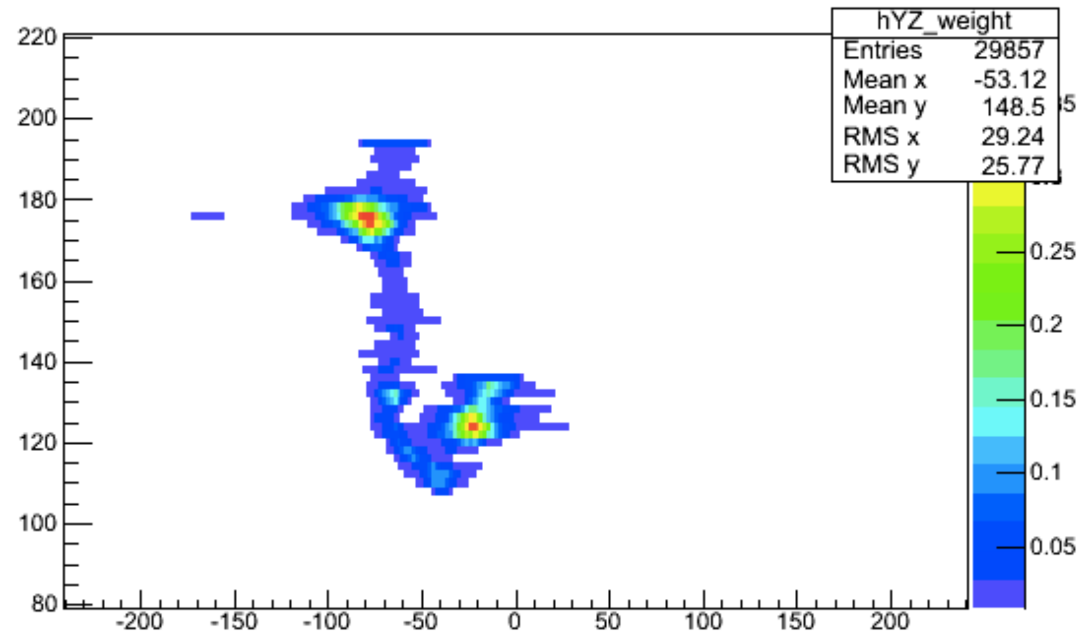
If ^{136}Ba-tagging can be implemented: $T_{1/2} = 1.6 \cdot 10^{28}$ yr

@next

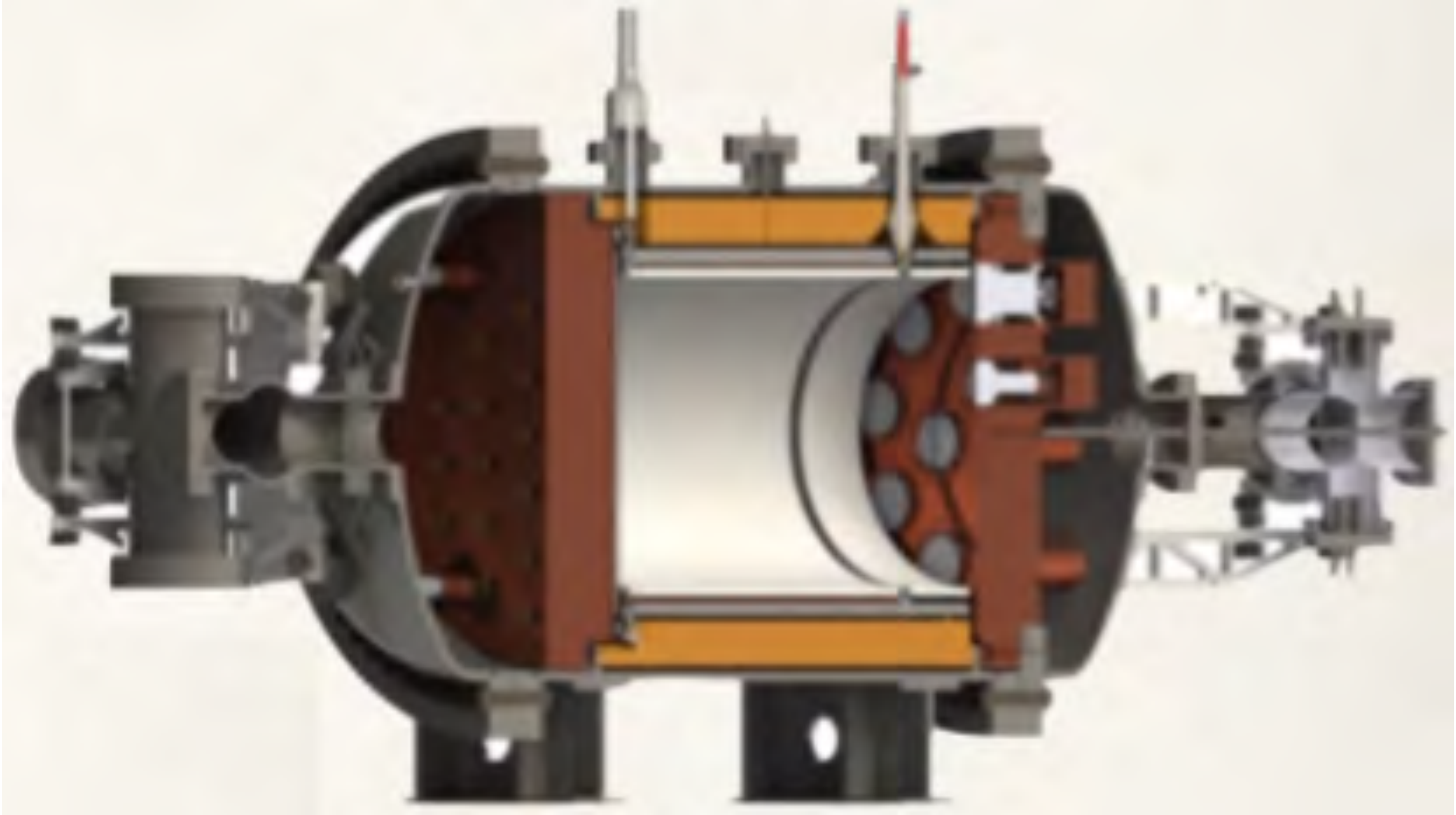


High pressure (10-15 bar) enriched Xe TPC

- Based at LNC
- Primary scintillation for energy: PMT
- Ionisation for tracking: SiPMs
- Very clear topological signature

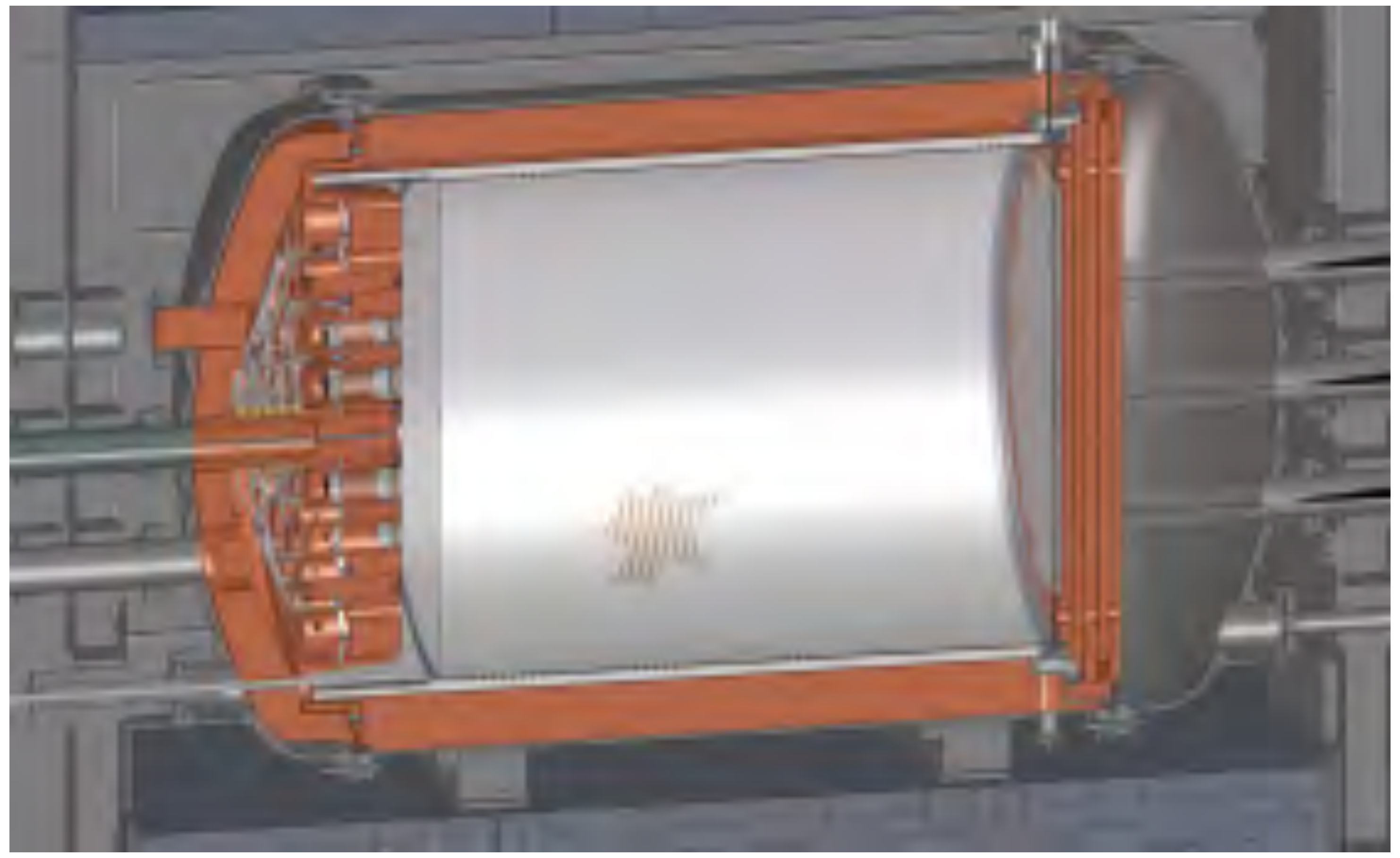


10 kg prototype with natXe



- Working @ LNC
- FWHM < 1% FWHM in the ROI (< 25 keV)
- Enriched Xe run: start in 2018

NEXT 100



- Commissioning in 2019
- 5 y sensitivity:
  - $T_{1/2} > 9.8 \cdot 10^{25}$ y
  - $m_{ee} < 46–170$ meV

NEXT 2.0

- Better tracking: He-Xe mixture
- Ton scale
- PM \to Si-PM
- Ba tagging

PandaX-III

Particle And Astrophysical Xenon Experiment III

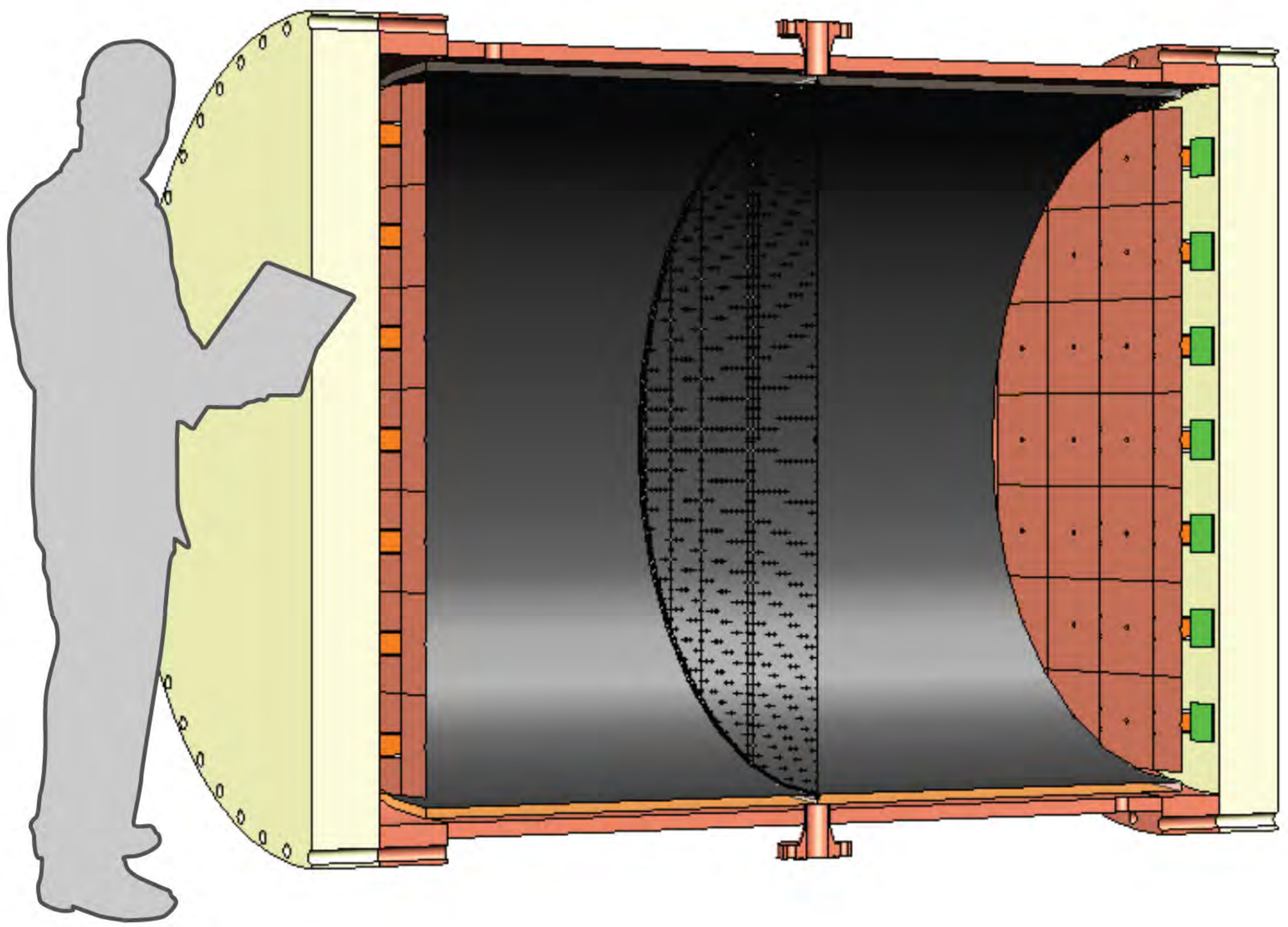
Based @ Jin-Ping underground Laboratory II (CJPL-II)

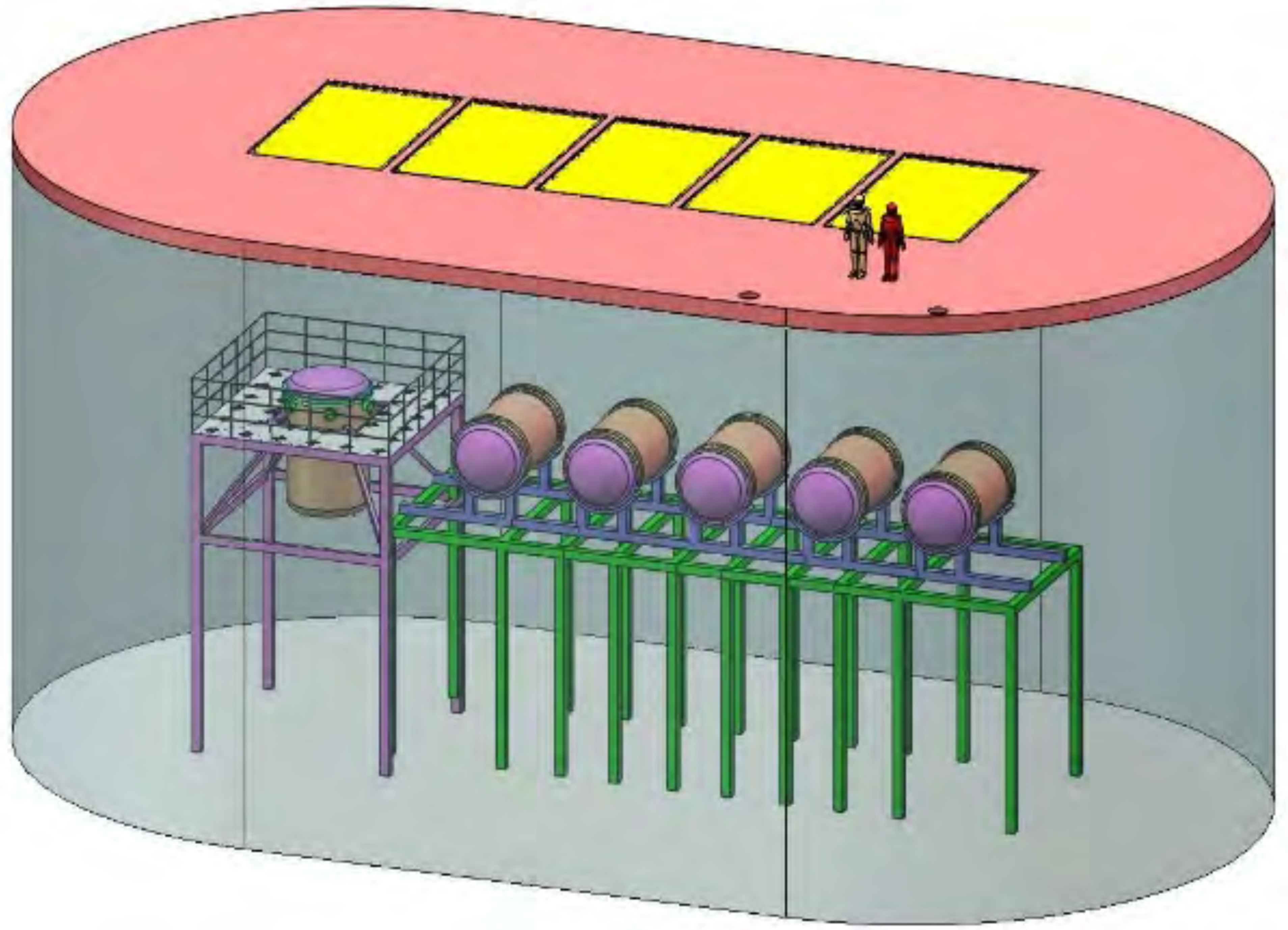
Phase I:

- high pressure gas TPC
- 200 kg of 90% enriched ^{136}Xe
- Microbulk Micromegas for charge readout
  - FWHM: 3%
  - Background index: $1 \cdot 10^{-4}$ c/keV/kg/y in the ROI

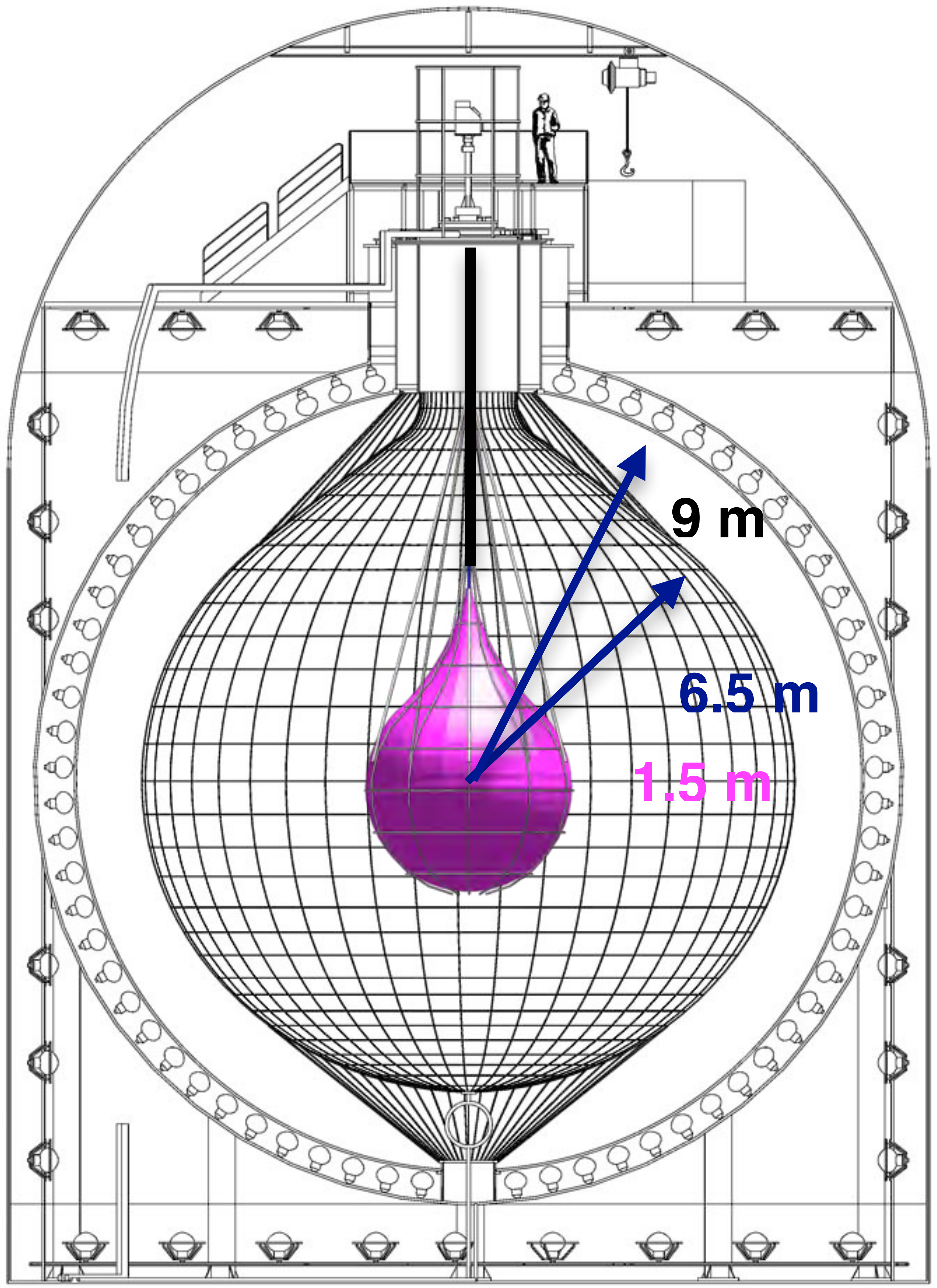
Ton-scale:

- Four more modules with upgraded charge readout and better low-background material screening.
  - FWHM: 1%
  - Background index: $1 \cdot 10^{-5}$ c/keV/kg/y in the ROI



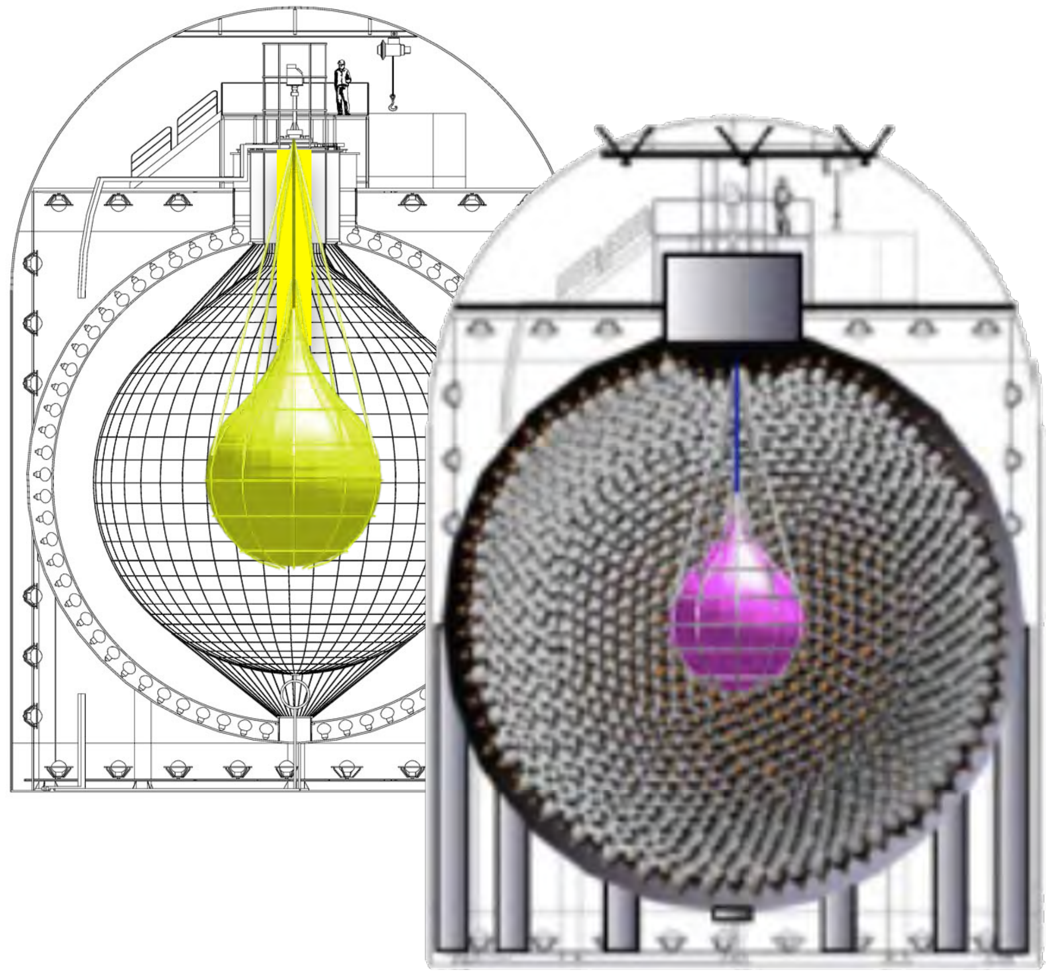


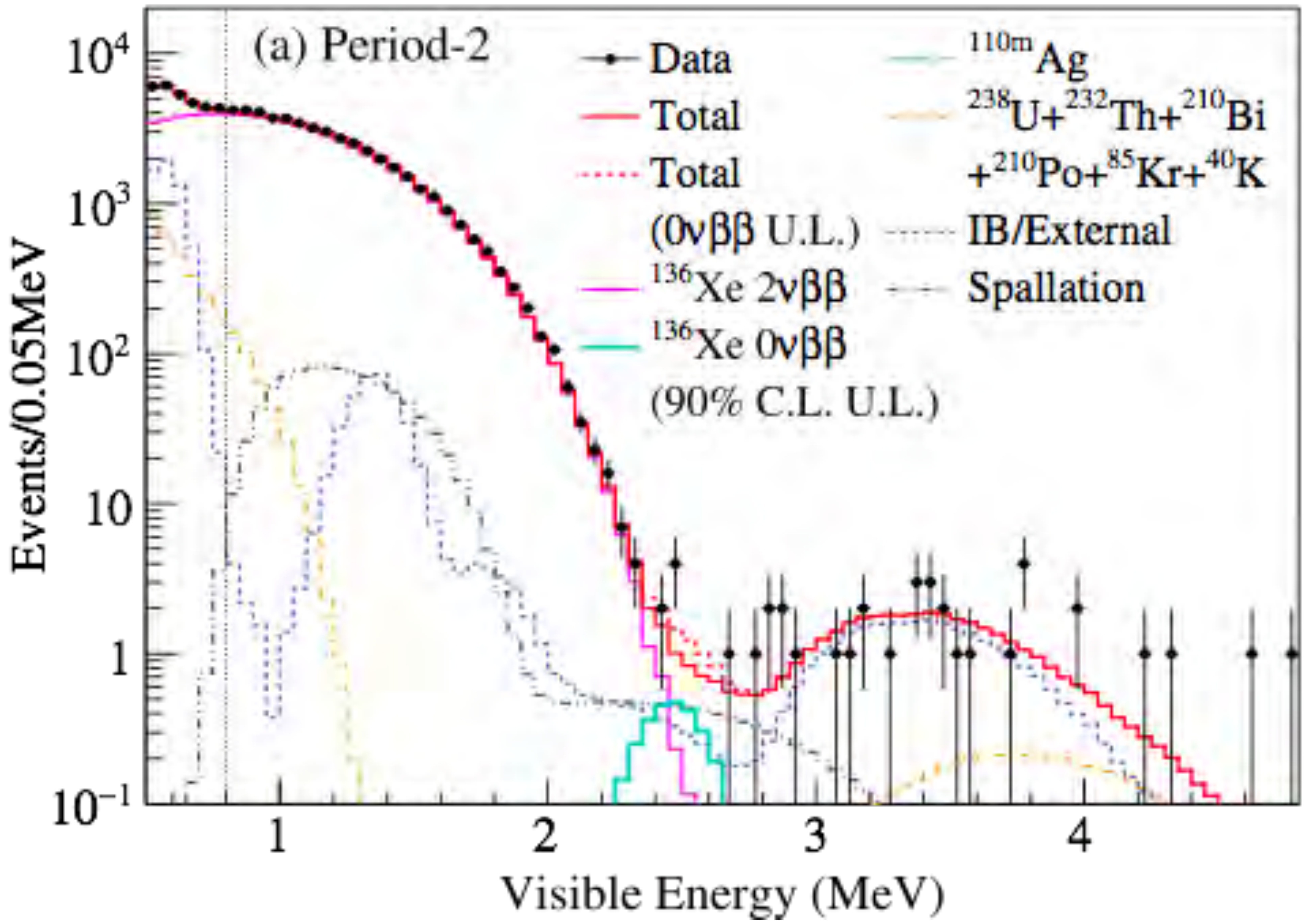
KamLAND-Zen

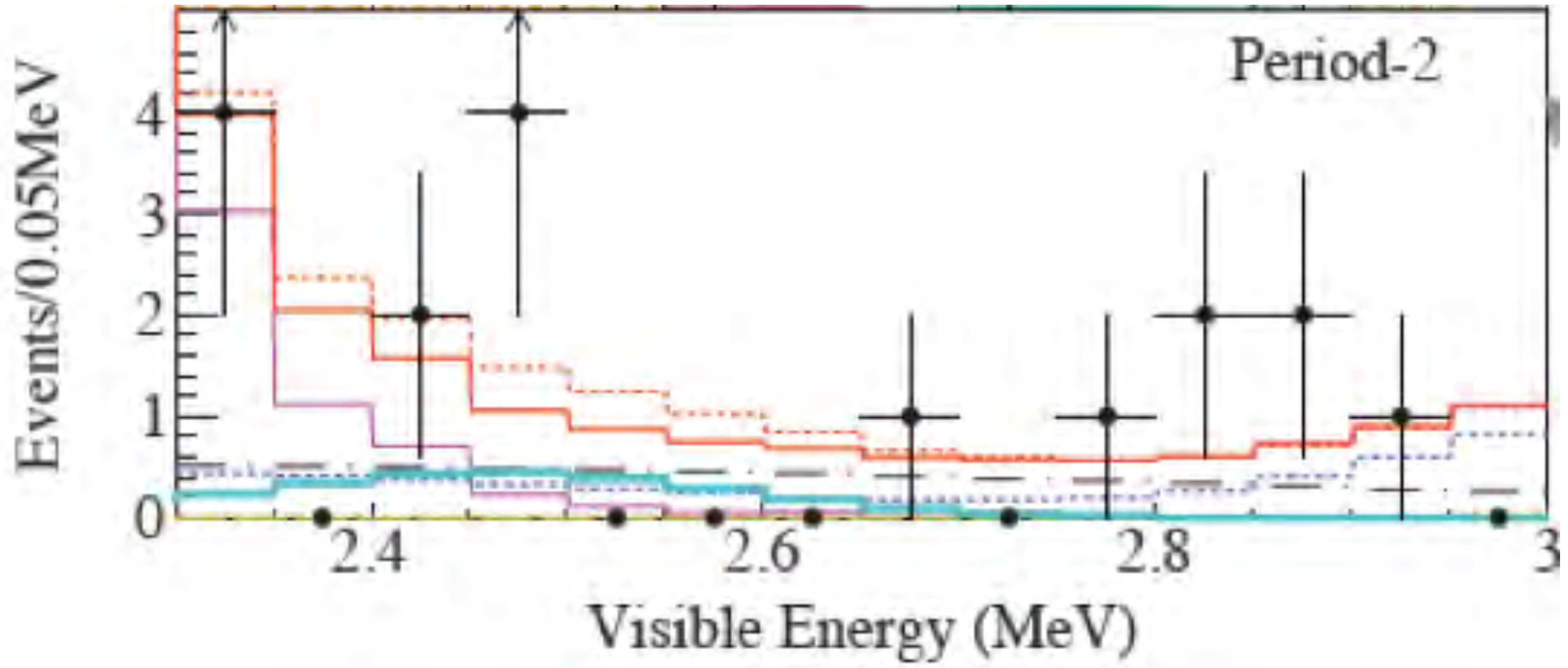


- Sensitivity:
  > 5.6·10^25 yr (90% C.L.)
- Unconstraint fit:
  > 9.2·10^25 yr (90% C.L.)
- Phase I + II:
  > 1.07·10^26 yr (90% C.L.)

- Phase III (2017 -):
  data taking with 750 kg enrXe (new balloon)



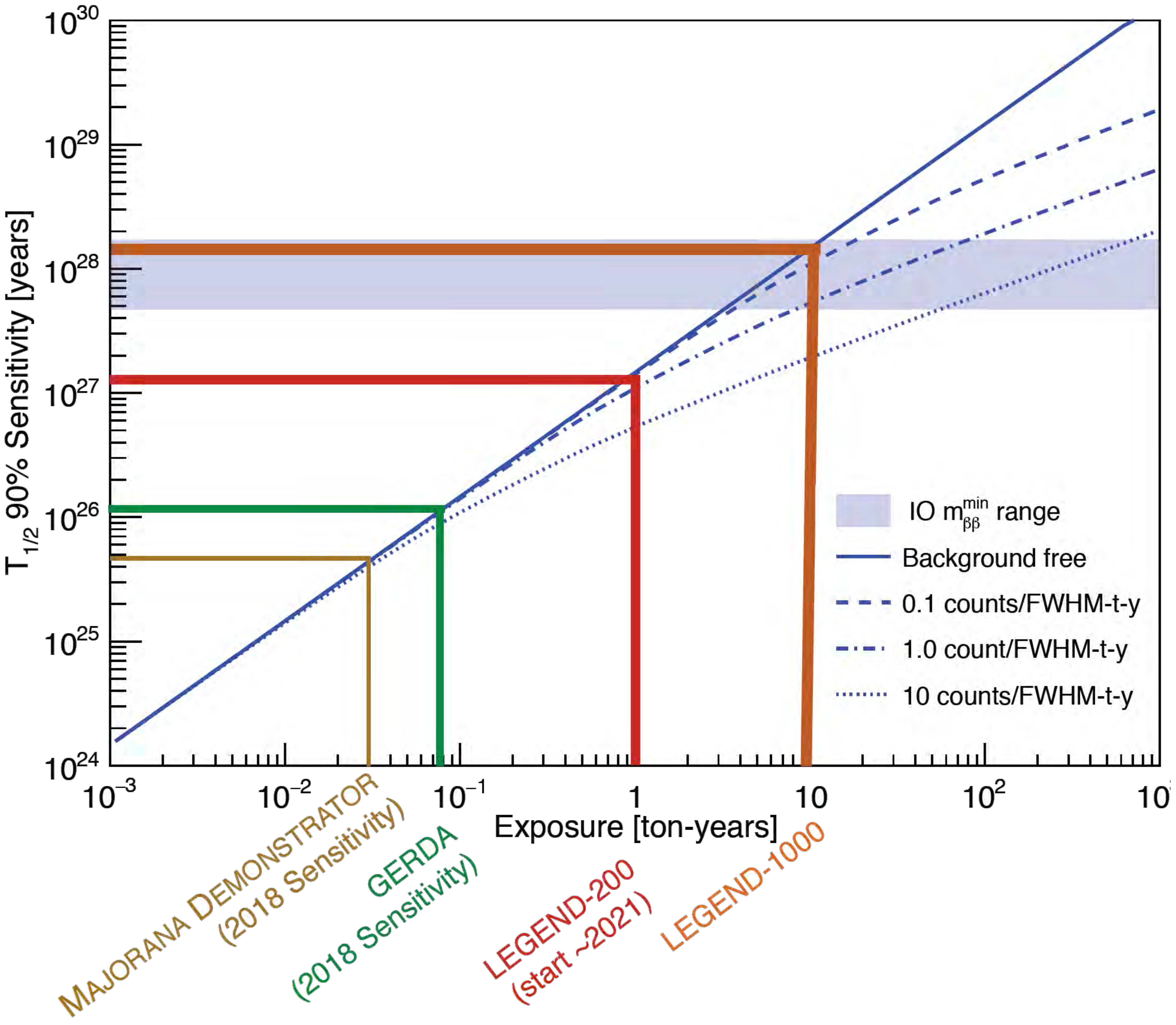




Phase-2: 2013/12/11 - 2015/10/27: **534.5 days (504 kg-yr)**

- KamLAND2-Zen with 1000 kg + proposed

LEGEND



First Stage:

- (up to) 200 kg ^{76}Ge in upgrade of existing infrastructure at LNGS
- BG goal 0.6 cts/(FWHM t yr)
- Data start ~2021
- Will use
    - existing MAJORANA & GERDA detectors (65 kg),
    - plus new detectors (135 kg)

Subsequent Stages:

- 1000 kg 76Ge (staged)
- BG goal: 0.1 cts/(FWHM t yr)
- Location: TBD

SNO setup and acrylic vessel filled with 780 tons of liquid scintillator

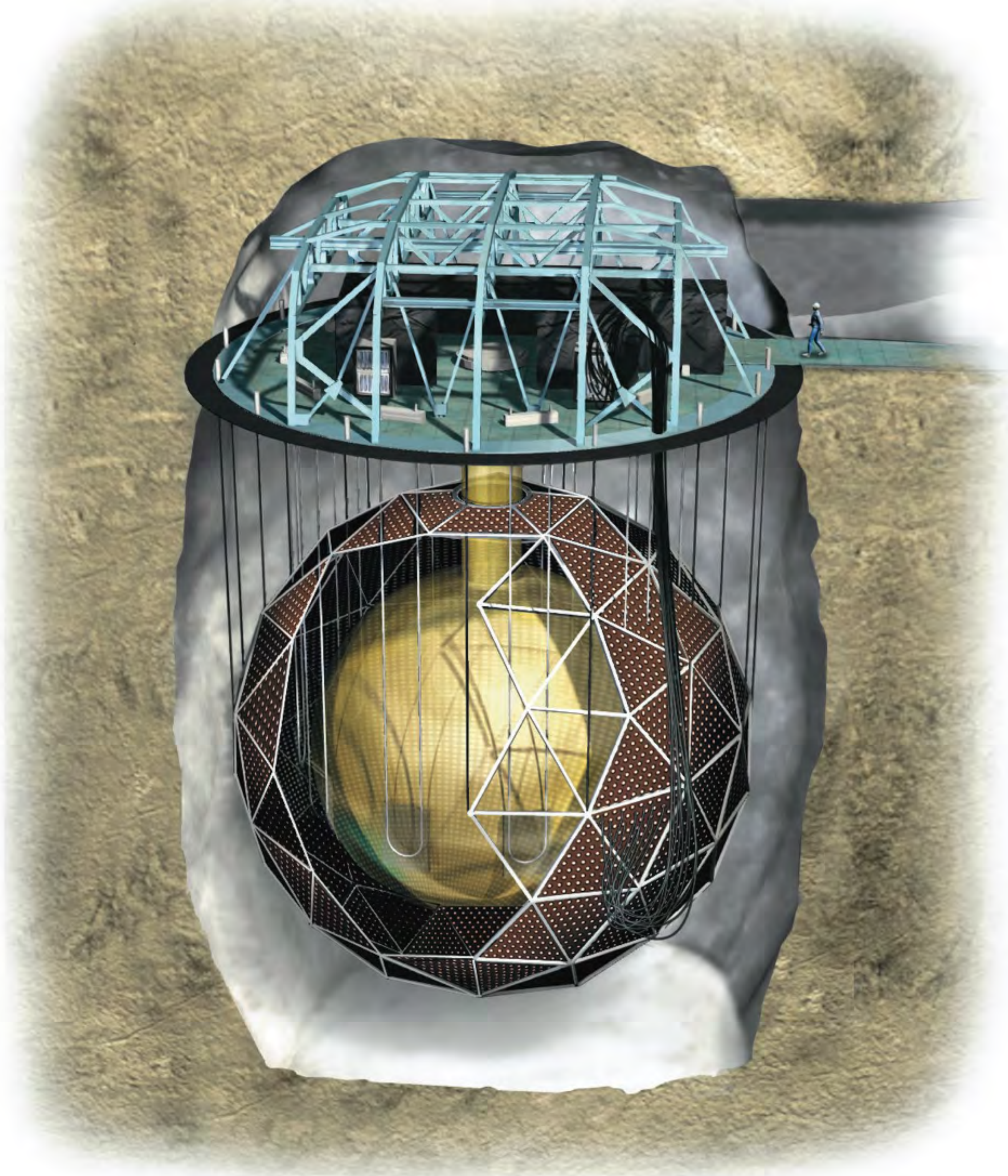
Phase I:

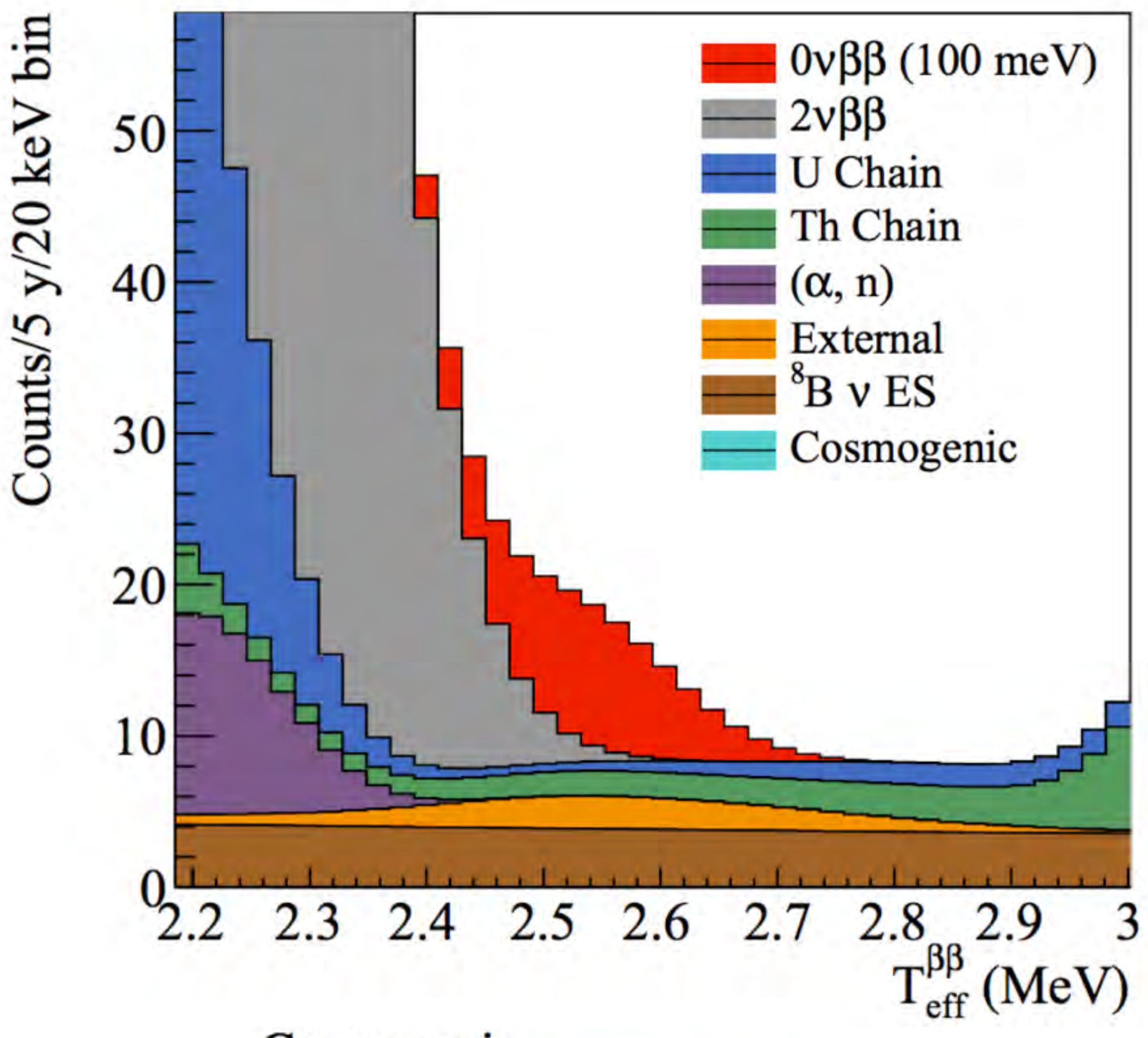
- 1.3 tons of natural Te
  - 0.5% mass loading
- FWHM: 190 keV
- 5 y sensitivity:
  - $T_{1/2} > 1.9 \cdot 10^{26}$ y
  - $m_{ee} < 35$–140 meV

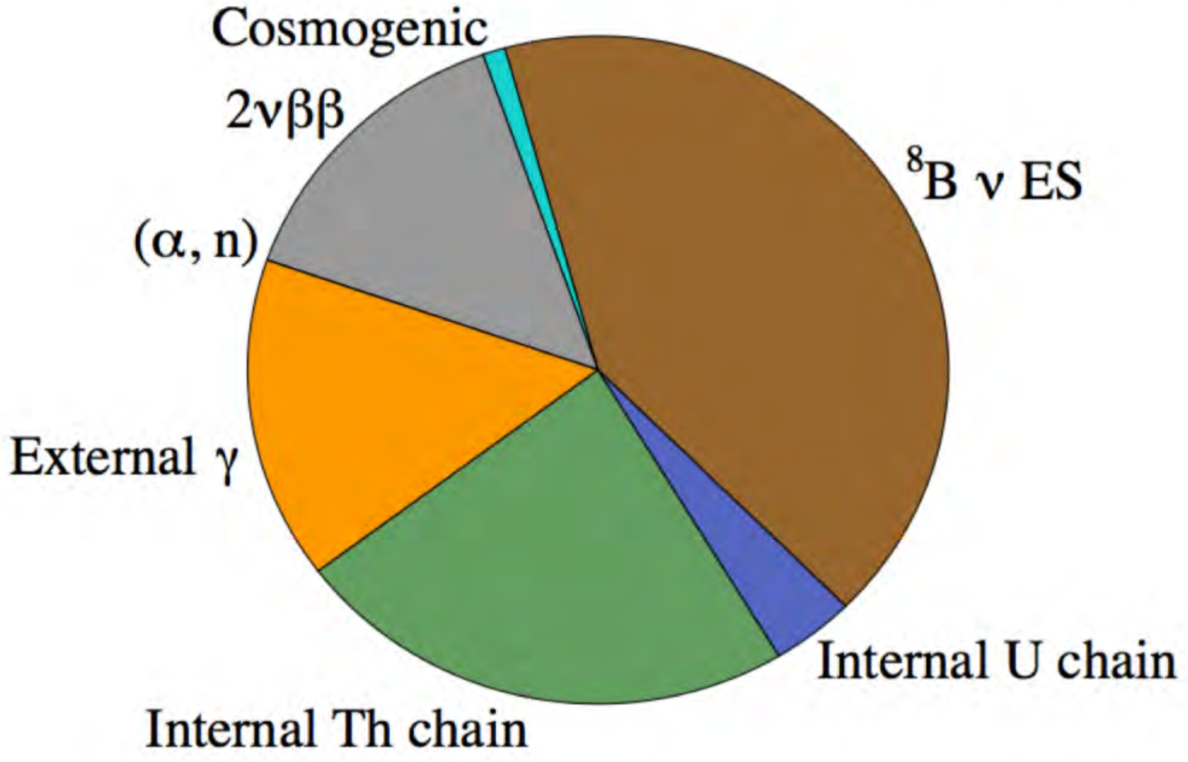
✦ Water fill: complete (Feb 2017)
✦ LS fill: July 2018
✦ Te loading: spring 2019

Phase II (ongoing R&D)

- Increase:
  - Te concentration, light yield, transparency ight detectors
- Sensitivity:
  - $T_{1/2} > 1 \cdot 10^{27}$ y
  - $m_{ee} < 15$–60 meV



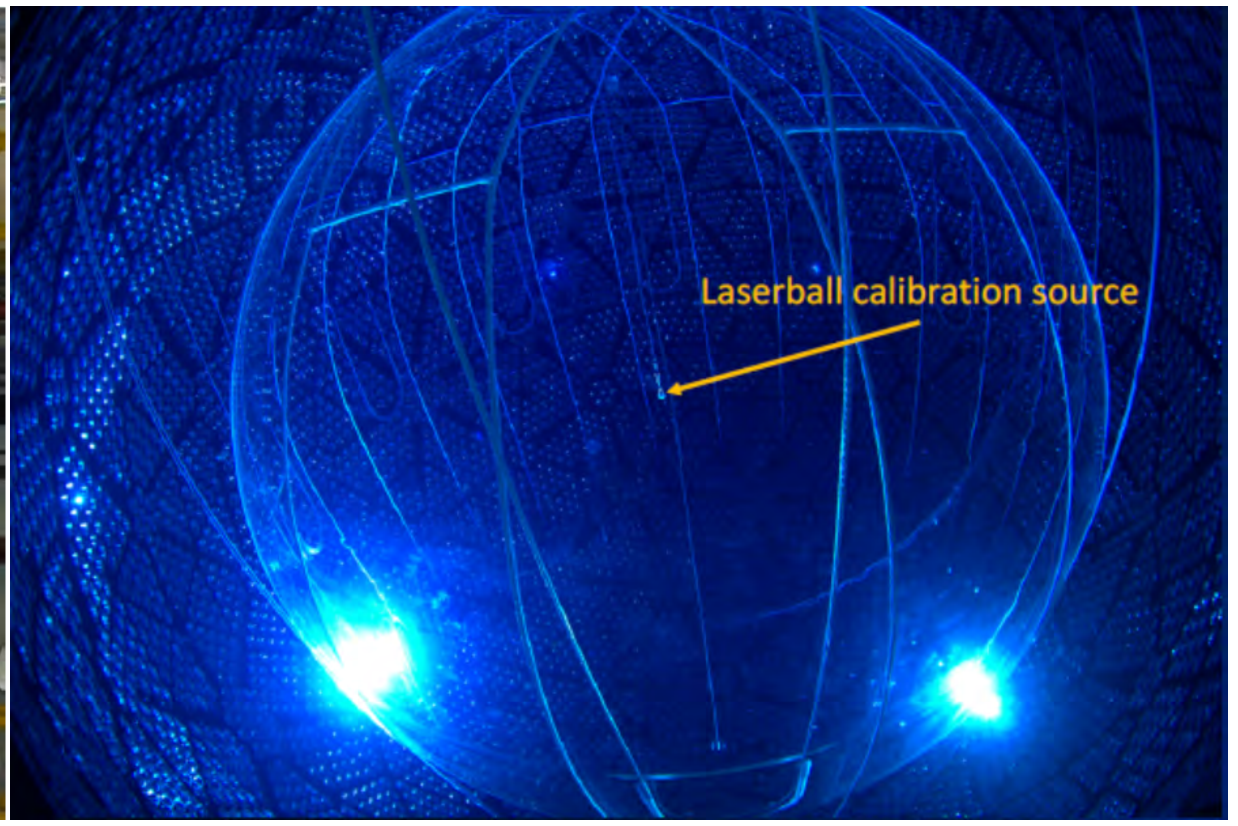




THEIA: new concept

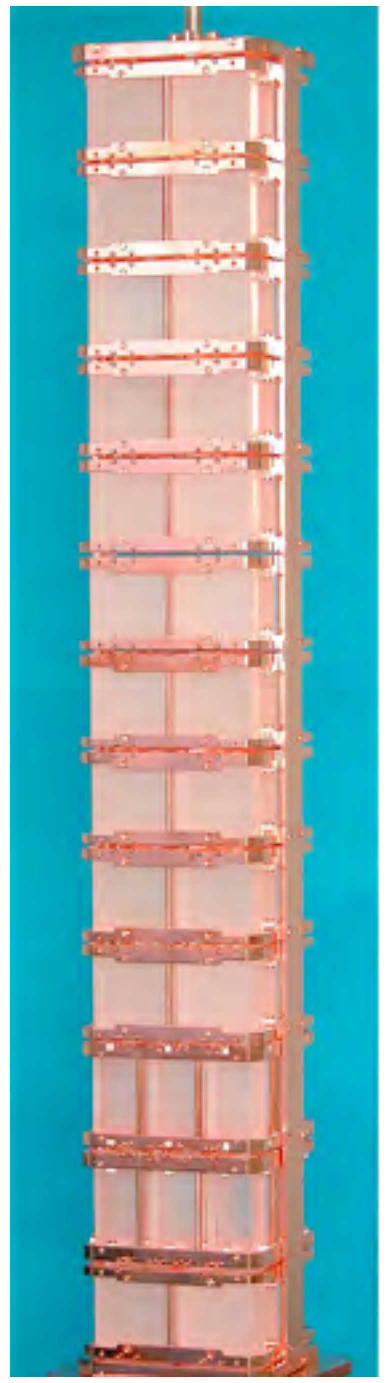
- 50 kton water-based liquid scintillator
- High coverage and fast photon detectors
- Deep underground
- 8-m radius balloon with high-LY LS
- 7-m fiducial, 3% natTe,
- Dominant background: ^{8}B solar n's

- Sensitivity 10 years:
  - $T_{1/2} > 1.1 \cdot 10^{28}$ y
  - $m_{ee} < 5$–18 meV

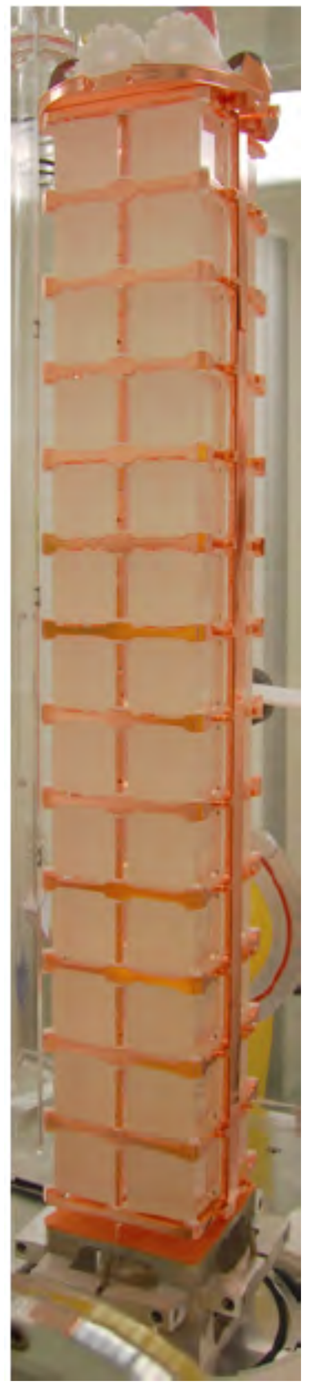


CUORE

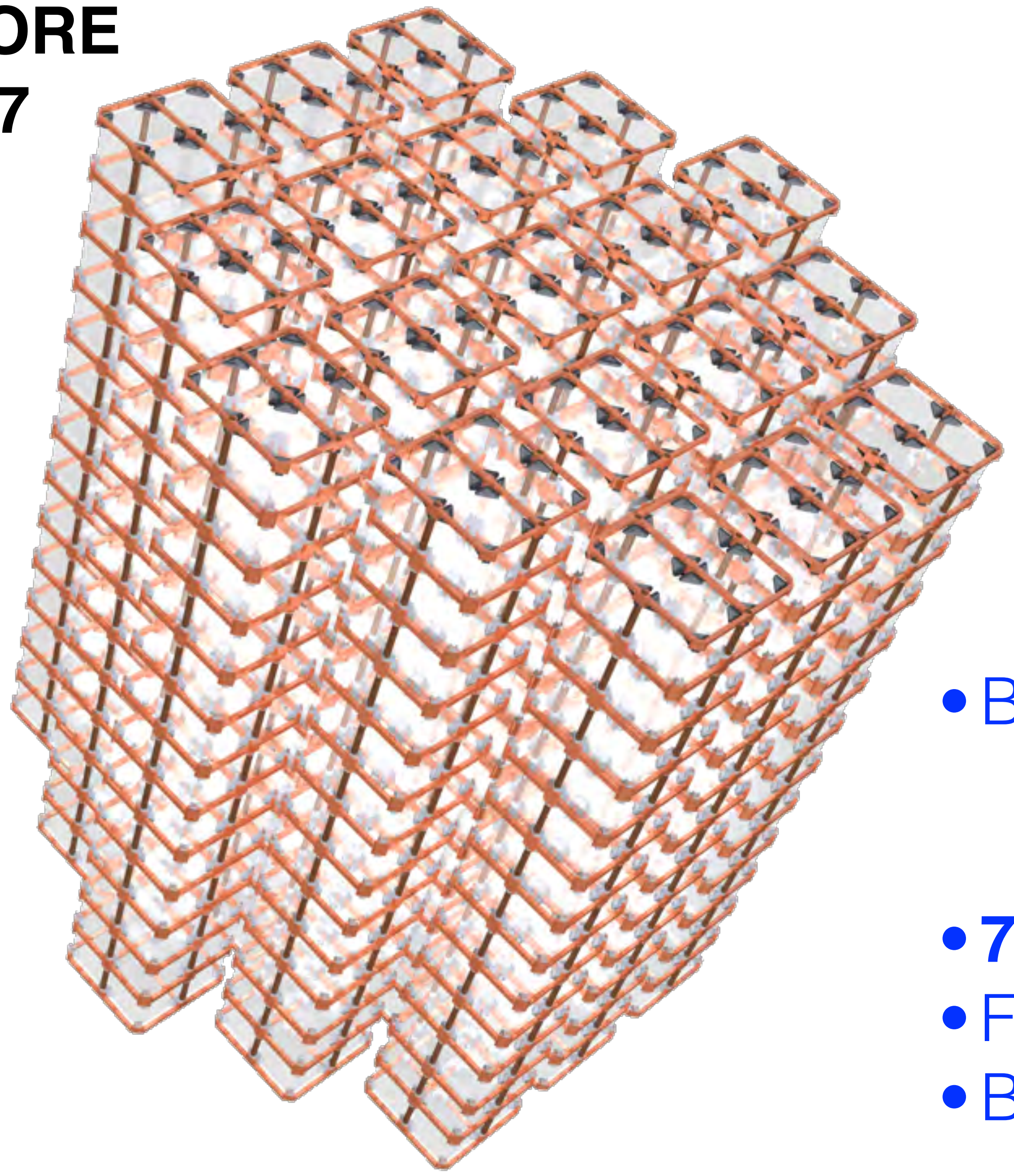
Cuoricino 2003

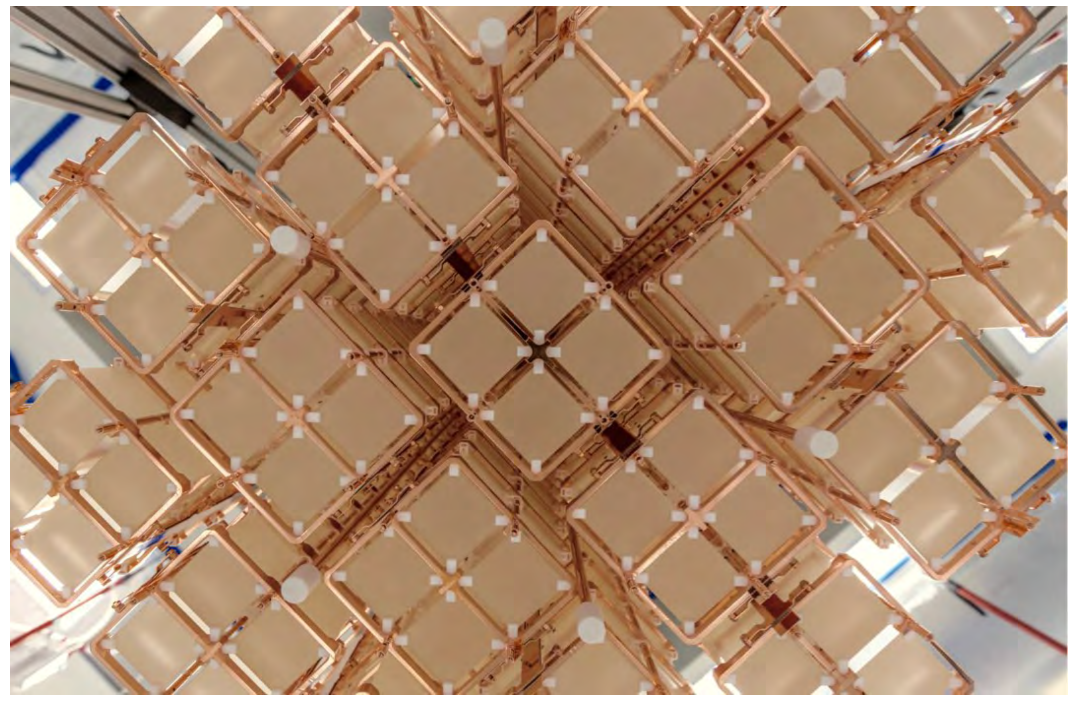


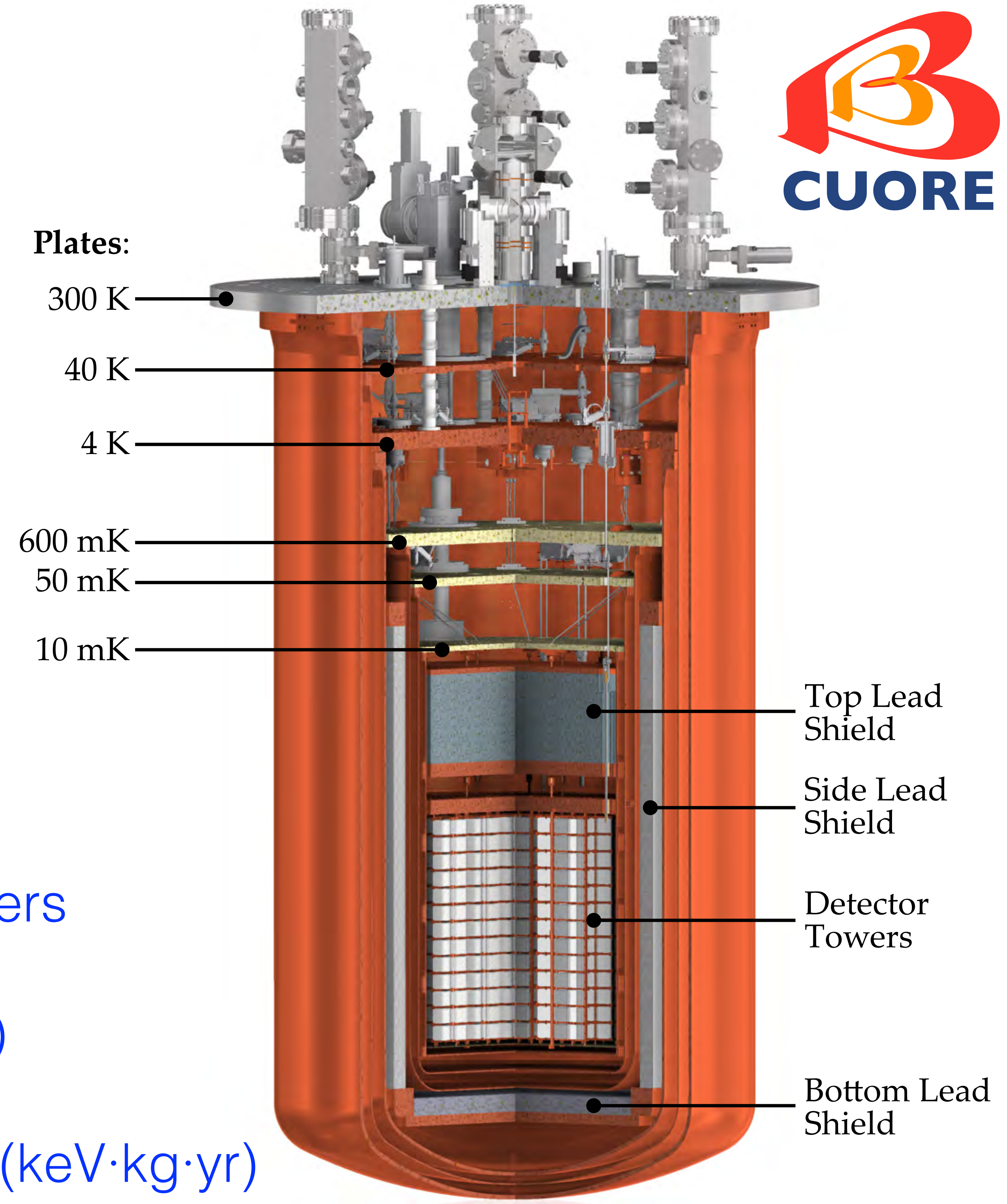
CUORE-0 2012



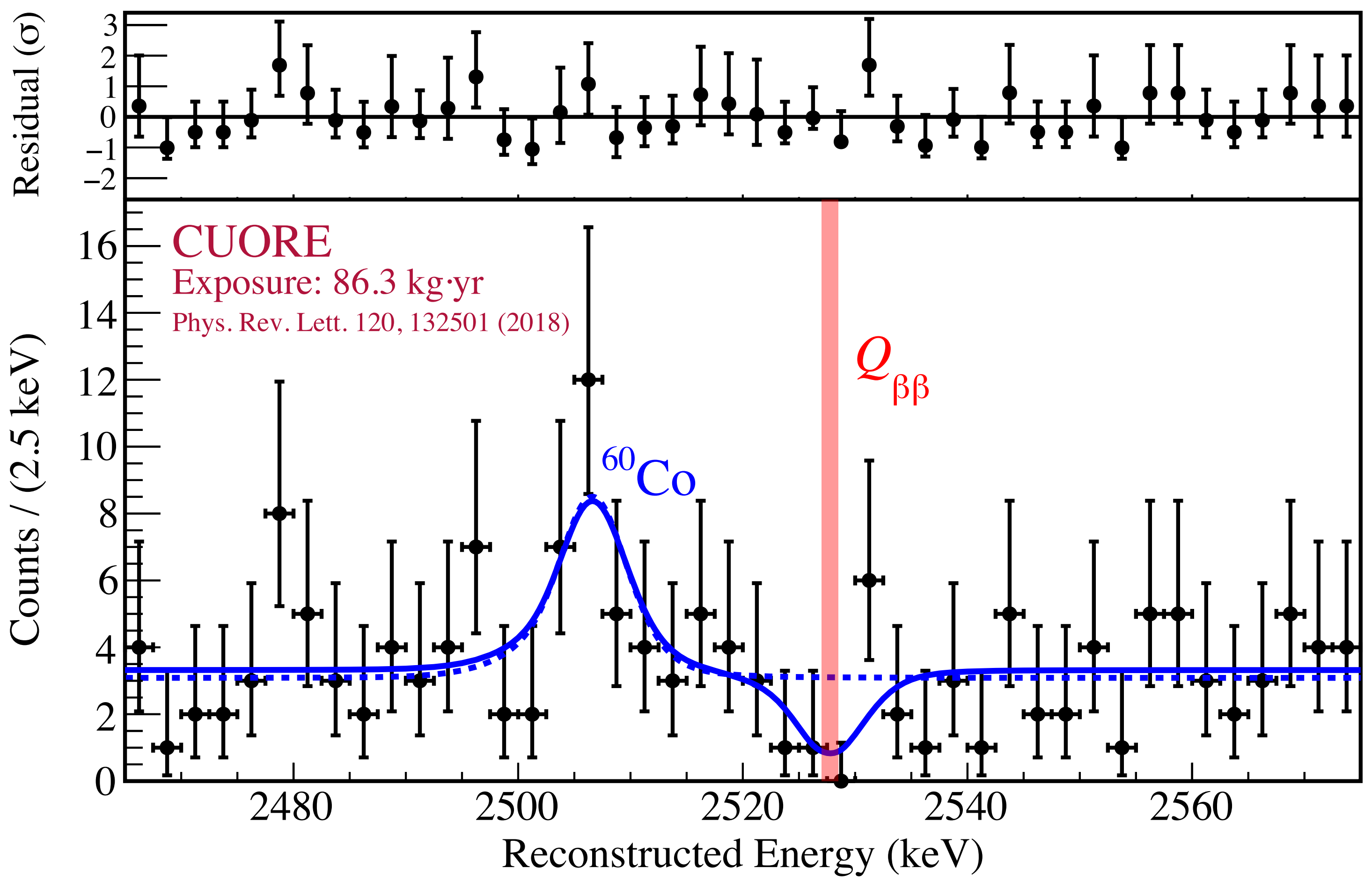
CUORE 2017







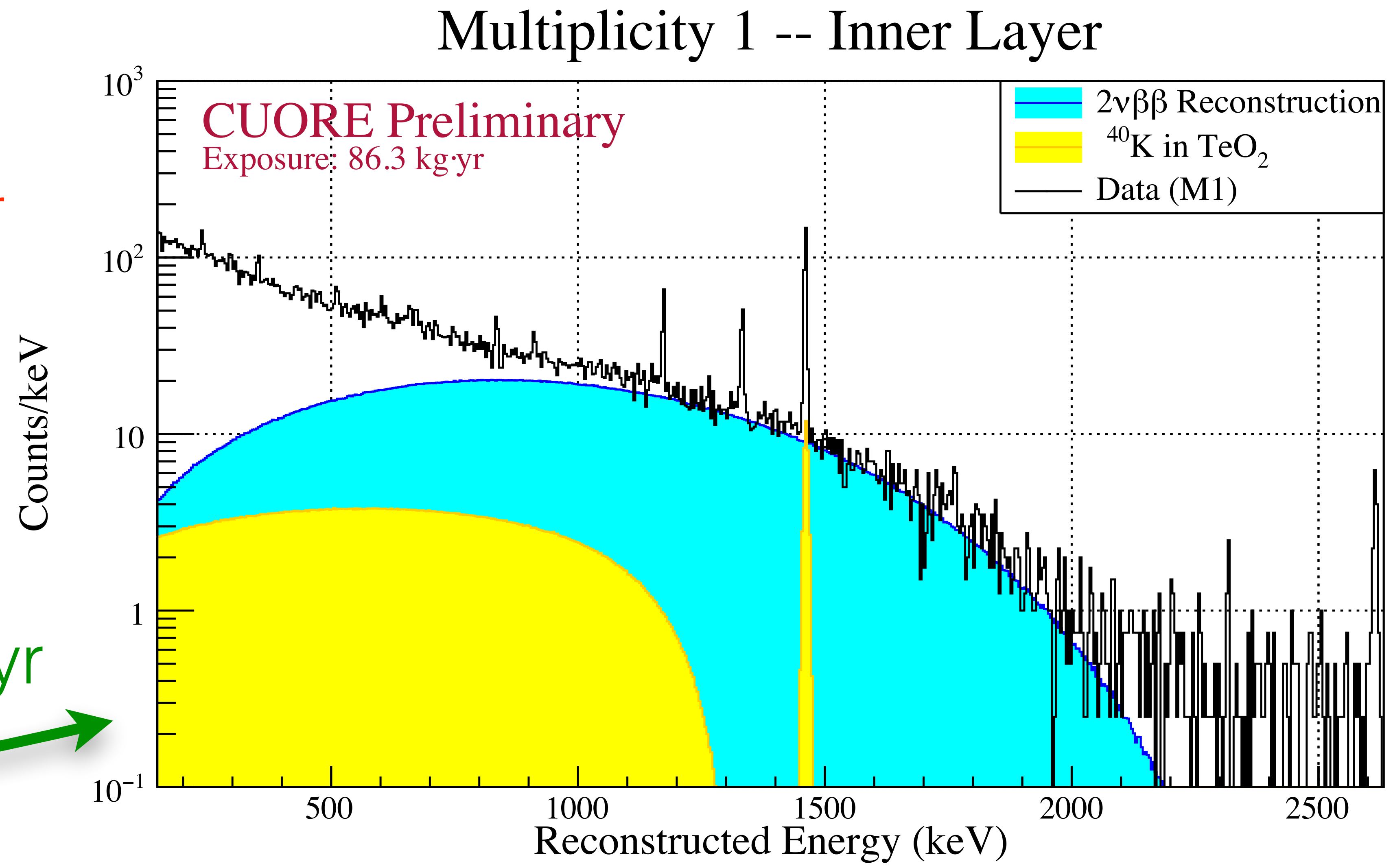
- Based @ LNGS
  - 988 TeO_2 crystals arranged in 19 towers
  - dedicated cryogen-free cryostat
- **742 kg of** natural TeO_2 (206 kg of ^{130}Te)
- FWHM: **7.7 keV** FWHM (ROI)
- Background index: **(1.4 ± 0.2)·10^{-2}** cnts/(keV·kg·yr)



- Exposure: 86.3 kg(TeO_2)·yr
- Combined limit with CUORE-0 and Cuoricir
  - **$T_{1/2}(0\nu) > 1.5 \cdot 10^{25}$ yr (90%C.L.)**
  - **$m_{ee} < 110–520$meV**

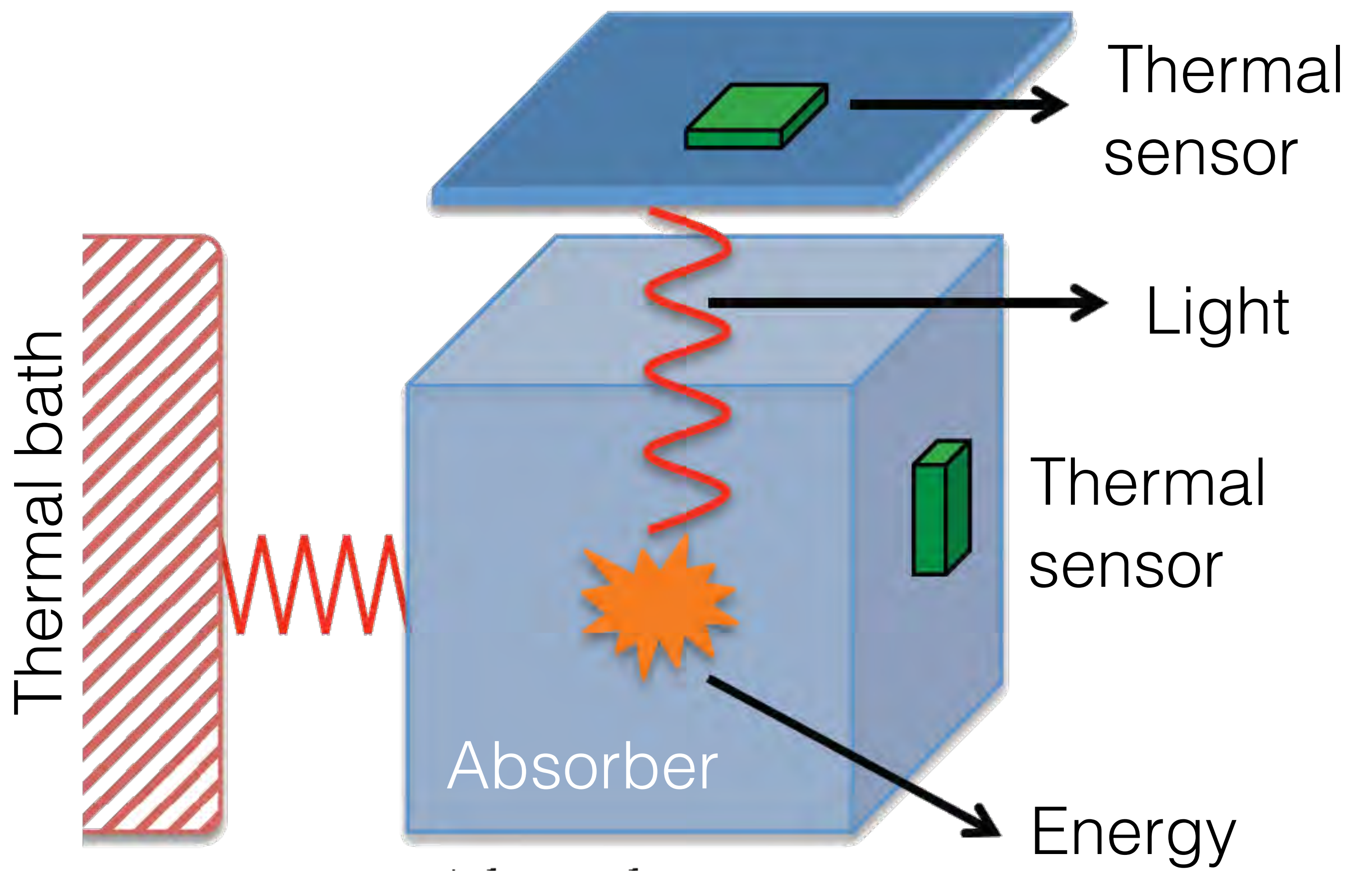
Phys. Rev. Lett. 120, 132501 (2018)

- $T_{1/2}(2\nu) = [7.9 \pm 0.1(stat.) \pm 0.2(syst.)] \cdot 10^{20}$ yr



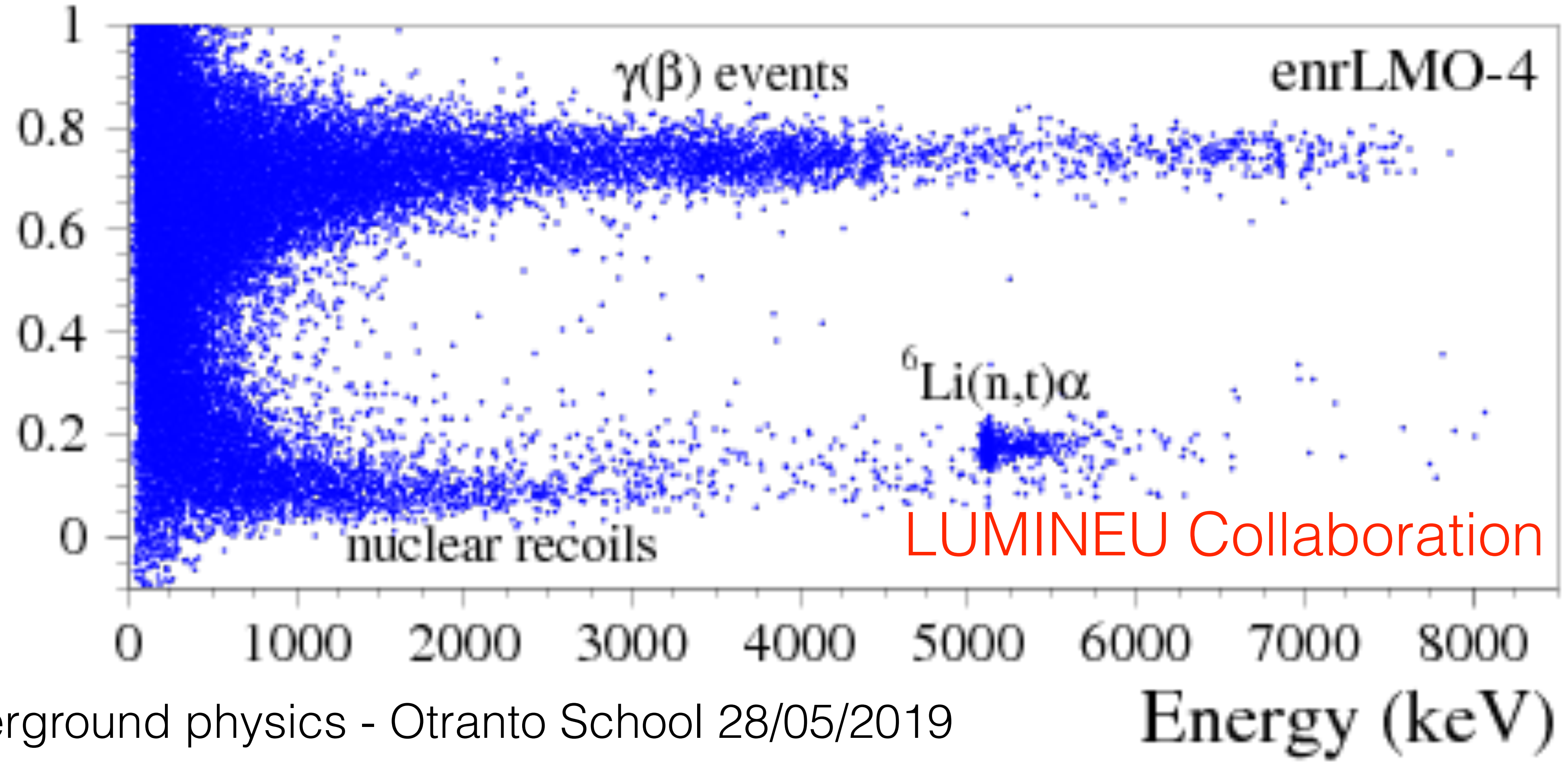
CUPID (**C**UORE **U**pgrade with **P**article

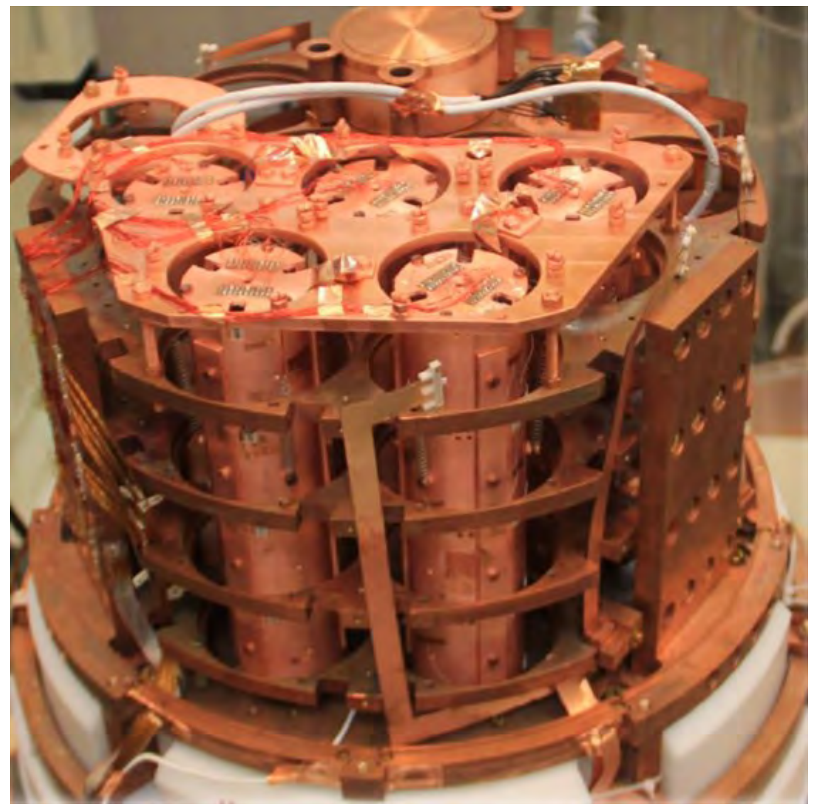
- Concept: α background rejection with particle ID
  - Add light read out (scintillation/Cherenkov)
  - Combine energy resolution of bolometers with background discrimination of a dual channel detector

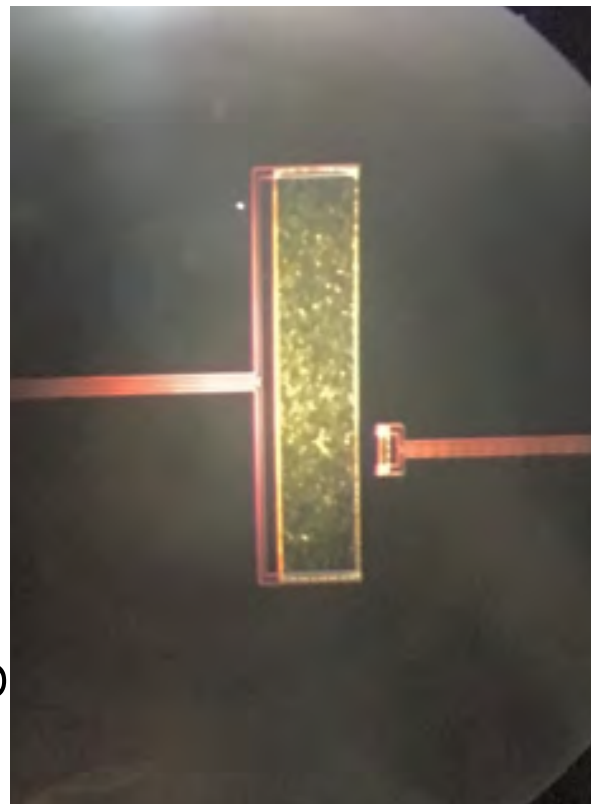


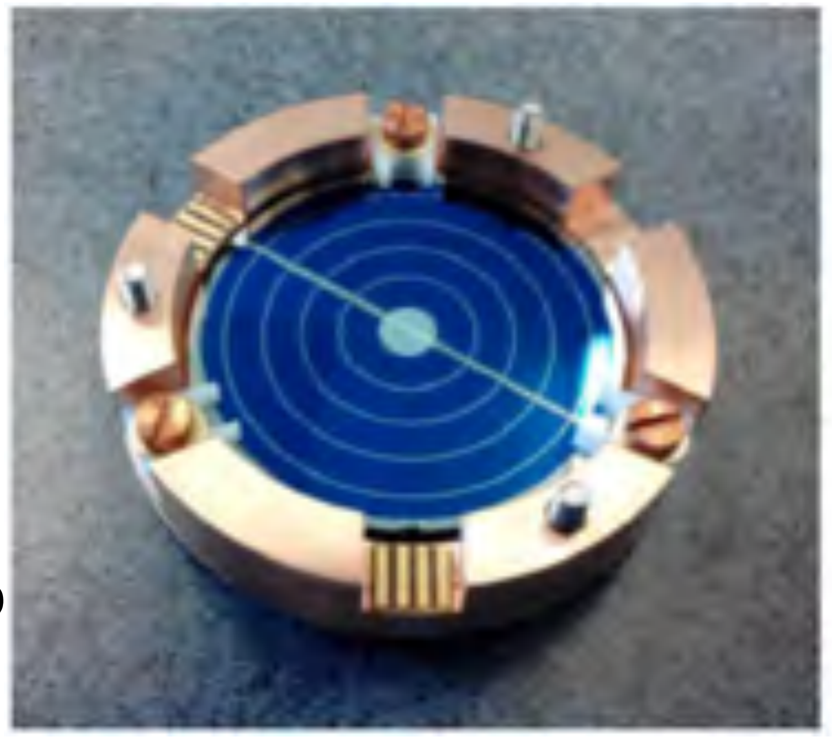
- Light emitting bolometers
- CUORE cryostat
- Nearly zero background goal: ~ 0.1 cnts/(ROI·yr)
- Worldwide effort focused on demonstrating readiness to construct a tonne-scale bolometric experiment

- Concept proved in a number of:
  - small scale detectors
  - larger scale demonstrators









- Li_2MoO_4 scintillating bolometers identified as a promising baseline
- Enriched TeO_2 is a mature viable alternative

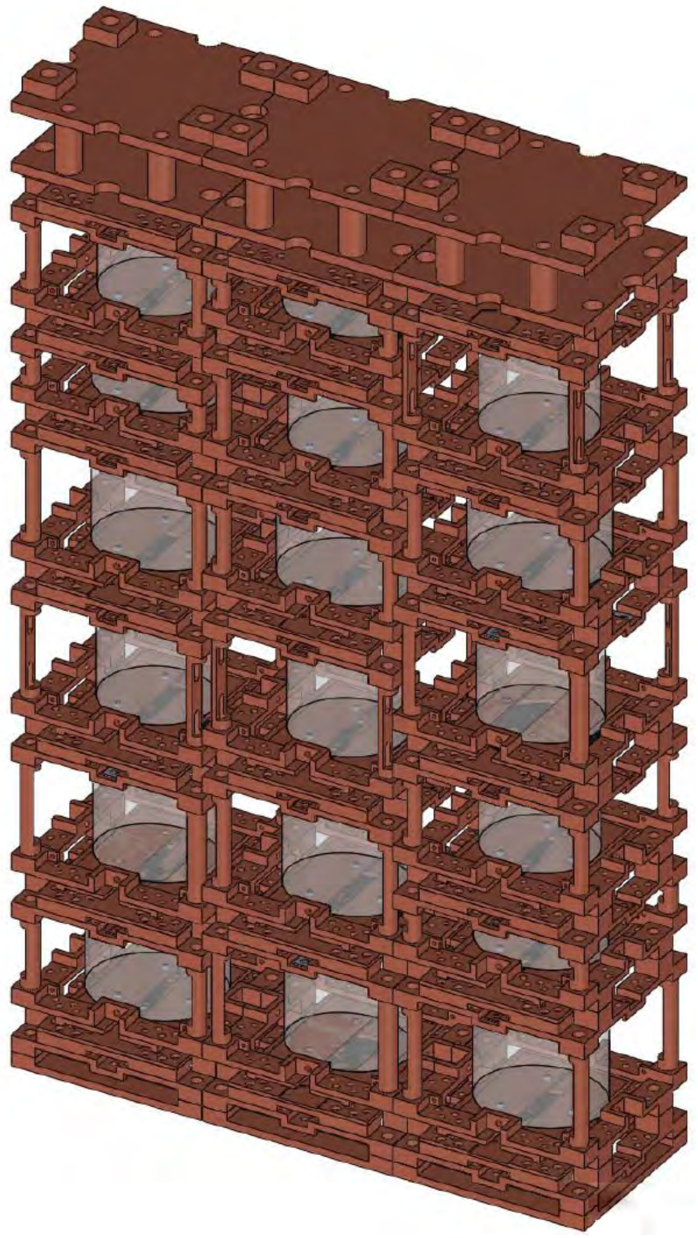
AMoRE

Concept :scintillating bolometers based on $Ca^{100}MoO_4$ (Ca depleted from ^{48}Ca)

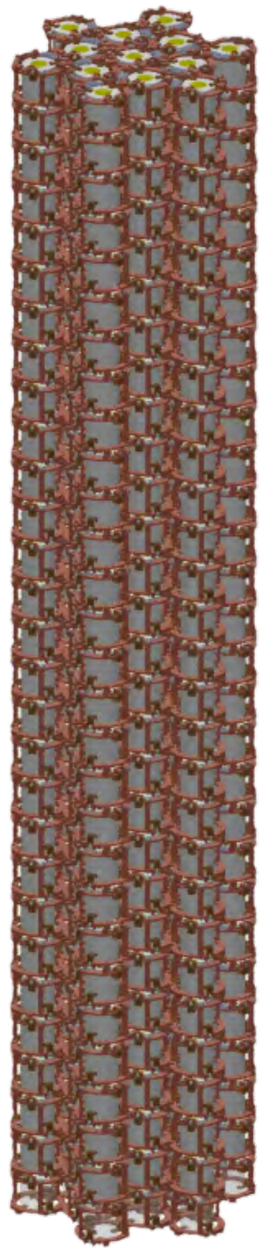
- AMORE-I @ Y2L with CaMoO4 (also ZMO, LMO, ...)
- AMORE-II @ new larger lab (ARF) with $\mathbf{X}^{100}MoO_4$ (**X**=Li, Na, ^{40}Ca, ...)
- 5 y sensitivities:
  - AMORE-I: $T_{1/2} > 10^{25}$ yr, $m_{ee} < 120–200$ meV
  - AMORE-II: $T_{1/2} > 10^{26}$ yr, $m_{ee} < 17–30$ meV

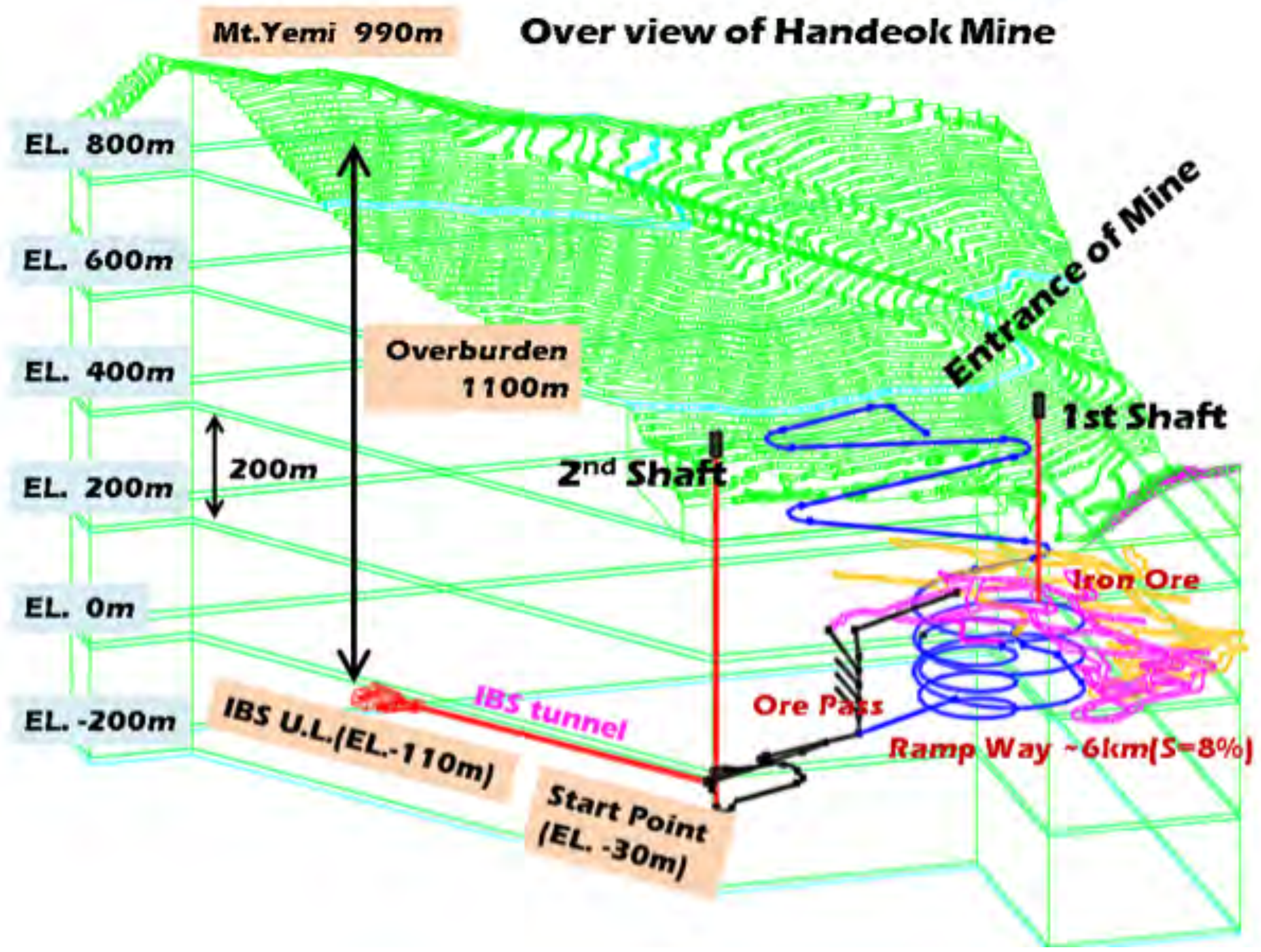
AMoRE-Pilot
~1.8 kg
2016-2017

AMoRE-I
5-6 kg
2018



AMoRE-II
200 kg
2020



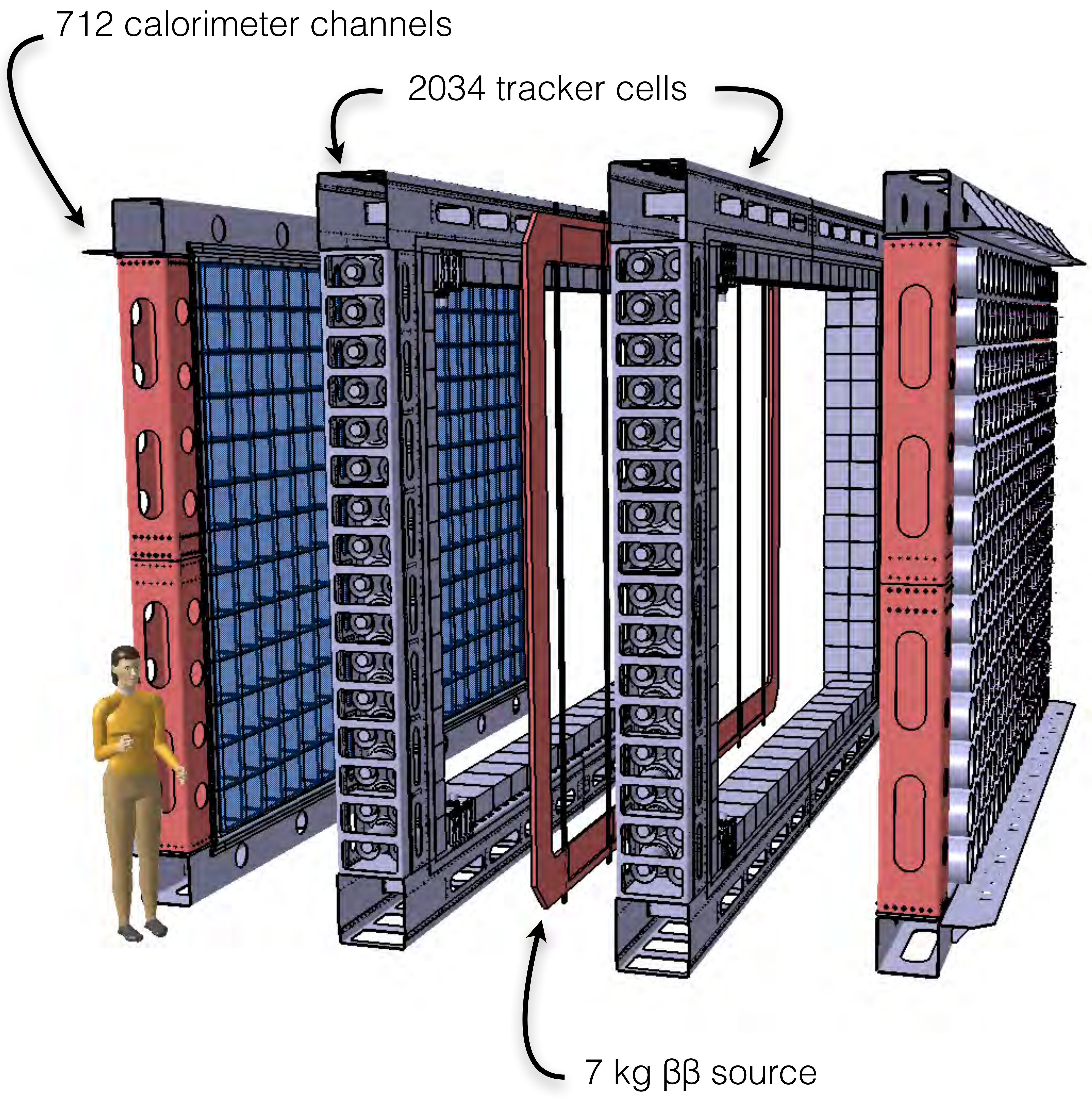


SuperNEMO

- Unique of the inhomogeneous approach experiments
- Built on the succesfull NEMO-3 experiment
- Based @ LSM
- Main advantage: full topological reconstruction:
  - crucial in case of discovery
  - easier access to other physics channels
- Total isotope mass: ~100kg of ^{82}Se (20 modules)
- Sensitivity: ~10^{26} yr

- SuperNEMO demonstrator expected start in 2018:
  - 7 kg of ^{82}Se.
  - 2.5 y sensitivity: $6 \cdot 10^{24}$ y

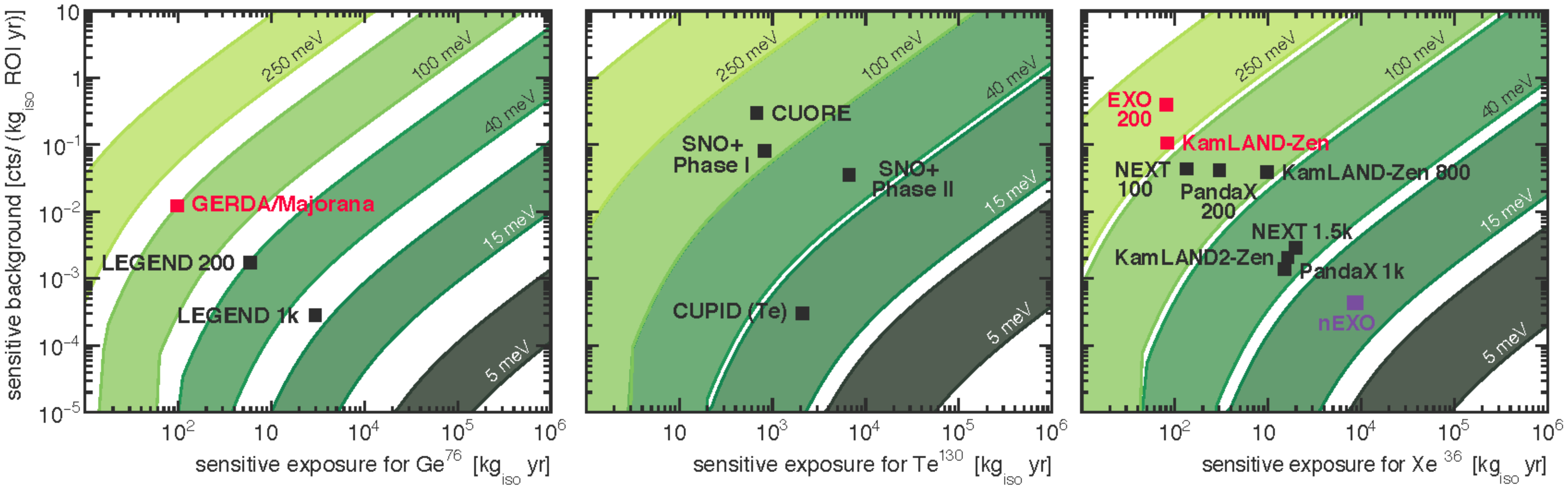
- Plans to move to ^{150}Nd



Discovery potential

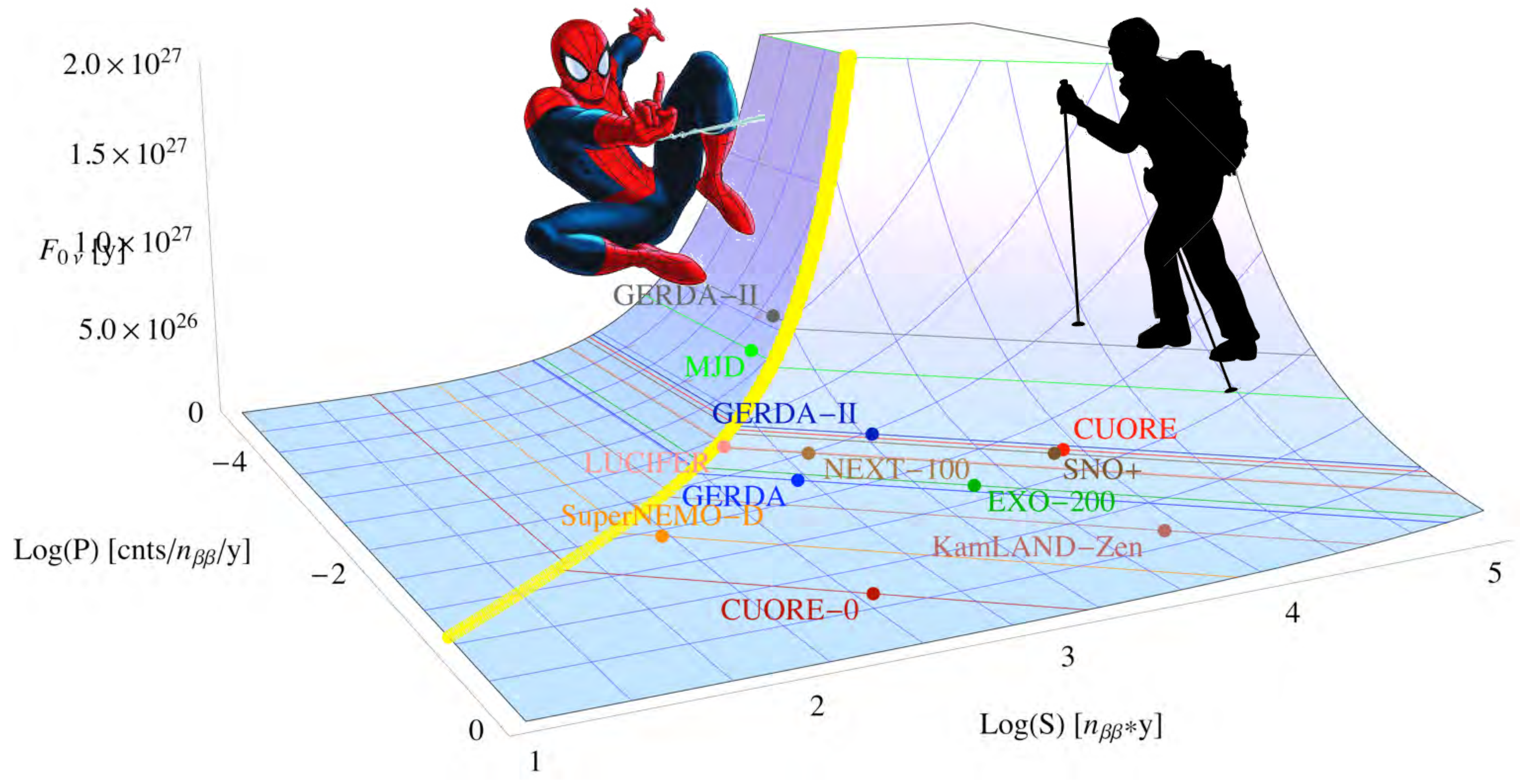
Discovery potential estimates for various proposals, assuming

- Type I see-saw
- free value of g_A
- Bayesian analysis with flatly distributed priors



Agostini, Benato, Detwiler, PRD 96 (2017) 053001 also A. Caldwell et al., PRD 96 (2017) 073001

The sensitivity hill



↑ = Direction of maximum increase of $F^{0\nu}$

$$N_B = S \cdot P \equiv 1$$
$$\mathcal{S}_{FB} \sim \sqrt{\frac{S}{P}}$$
$$\mathcal{S}_{ZB} \sim S$$

Transition region

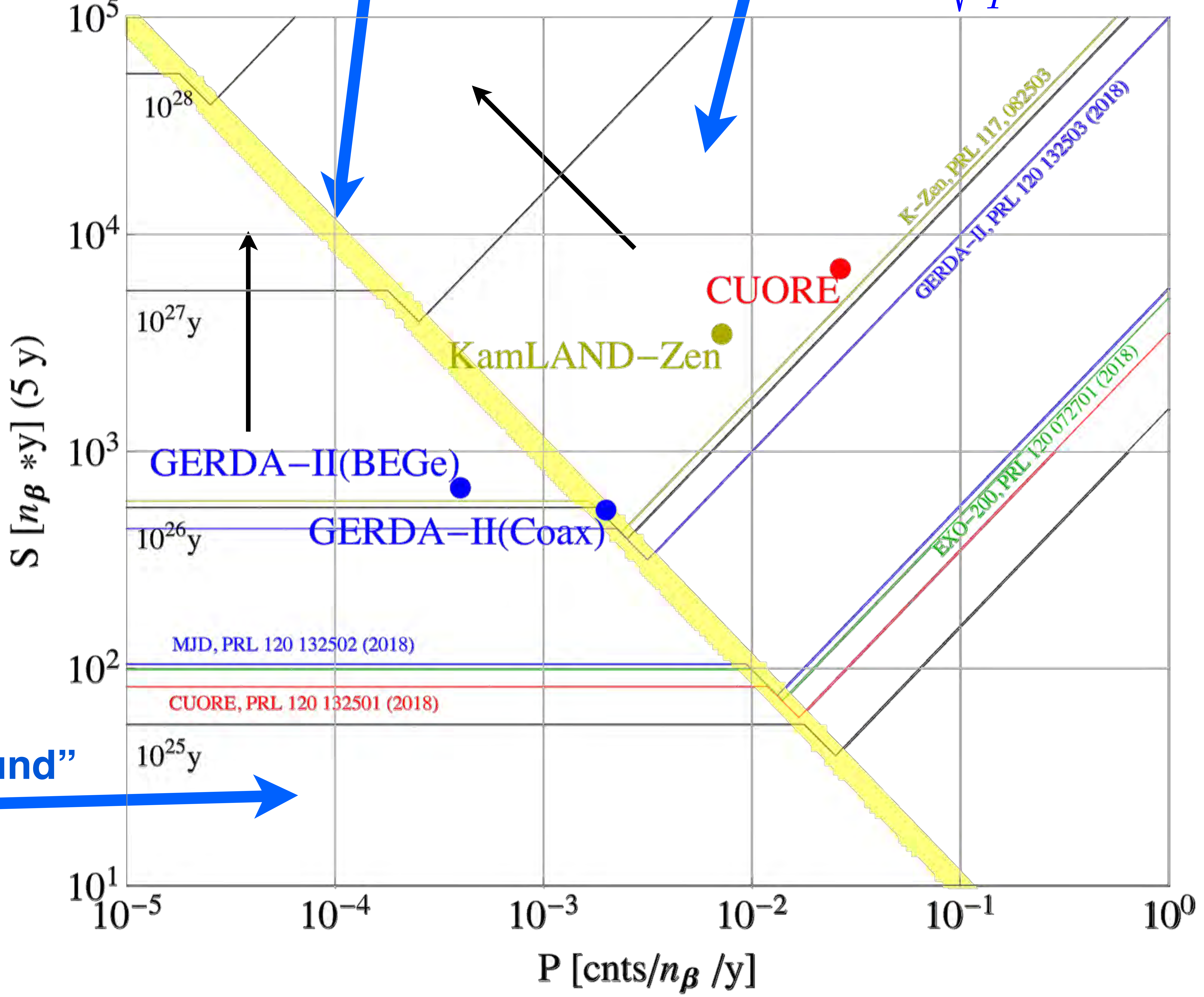
$N_B = S \cdot P \equiv 1$

“Finite background” region

$\mathcal{S}_{FB} \sim \sqrt{\frac{S}{P}}$

“Zero background” region

$\mathcal{S}_{ZB} \sim S$



Biassoni et al., arXiv:1310.3870

Fixed budget

- On a large scale, factors like cost and time can become important.
- Enrichment is a common request. Let's assume it accounts for half of the cost.
- Let's also assume g_A=1.25 and request a background level such to maintain each isotope in the ZB condition.
- What is the reach of a 100M € experiment?

		Bkg [c/keV/kg/y]	FWHM [keV]	M_{iso} [ton]	$T^{1/2}_{0\nu}$ (ZB) [yr]	<$m_{\beta\beta}$> [meV]	a.i. [%]	Cost(iso) [€/g]	Prod. [ton/y]	Cost(nat) €/g	M_{tot} [ton]
LEGEND	76Ge	8.4E-05	3	0.71	6.99E+27	19	7.8	70	165	1.2	0.79
CUPID ZnSe	82Se	1.56E-05	10	0.71	6.32E+27	12	9.2	70	2275	0.8	1.28
CUPID ZnMO4	100Mo	1.94E-05	9	0.5	3.63E+27	15	7.6	100	266000	0.02	1.15
CUPID CdWO4	116Cd	3.19E-05	6	0.33	2.09E+27	26	9.6	150	22200	0.06	1.05
CUPID TeO2	130Te	8.35E-06	5	3.85	2.34E+28	6	34.2	13	150	0.03	4.79
SNO++	130Te	1.93E-07	270	3.85	5.37E+27	12	34.2	13	150	0.03	3.85
nEXO+	136Xe	5.52E-07	58	6.25	2.09E+28	7	8.9	8	50	1.2	6.25
Kam-Zen	136Xe	1.28E-07	250	6.25	1.25E+28	9	8.9	8	50	1.2	6.25
BEXT	136Xe	2.13E-06	15	6.25	1.25E+28	9	8.9	8	50	1.2	6.25

Fixed $\langle m_{\beta\beta} \rangle$ sensitivity

- Let’s revers our argument and design an experiment with a sensitivity $\langle m_{\beta\beta} \rangle$=10 meV ($g_A$=1.25 and a background level such to maintain each isotope in the ZB condition)
- What is its scale and cost?

		Bkg [c/keV/kg/y]	FWHM [keV]	M_{iso} [ton]	$T^{1/2}_{0\nu}$ (ZB) [yr]	Cost(iso) [M€]	a.i. [%]	Cost(iso) [€/g]	Prod. [ton/y]	Cost(nat) €/g	M_{tot} [ton]
LEGEND	76Ge	2.29E-05	3	2.62	2.57E+28	184	7.8	70	165	1.2	2.92
CUPID ZnSe	82Se	9.68E-06	10	1.03	9.16E+27	72	9.2	70	2275	0.8	2.07
CUPID ZnMO4	100Mo	7.73E-06	9	1.13	8.19E+27	113	7.6	100	266000	0.02	2.88
CUPID CdWO4	116Cd	4.27E-06	6	2.24	1.4E+28	336	9.6	150	22200	0.06	7.81
CUPID TeO2	130Te	2.27E-05	5	1.27	7.72E+27	17	34.2	13	150	0.03	1.76
SNO++	130Te	1.21E-07	270	5.53	7.72E+27	72	34.2	13	150	0.03	6.15
nEXO+	136Xe	9.36E-07	58	3.32	1.11E+28	27	8.9	8	50	1.2	3.68
Kam-Zen	136Xe	1.3E-07	250	5.53	1.11E+28	44	8.9	8	50	1.2	6.14
BEXT	136Xe	2.17E-06	15	5.53	1.11E+28	44	8.9	8	50	1.2	6.14