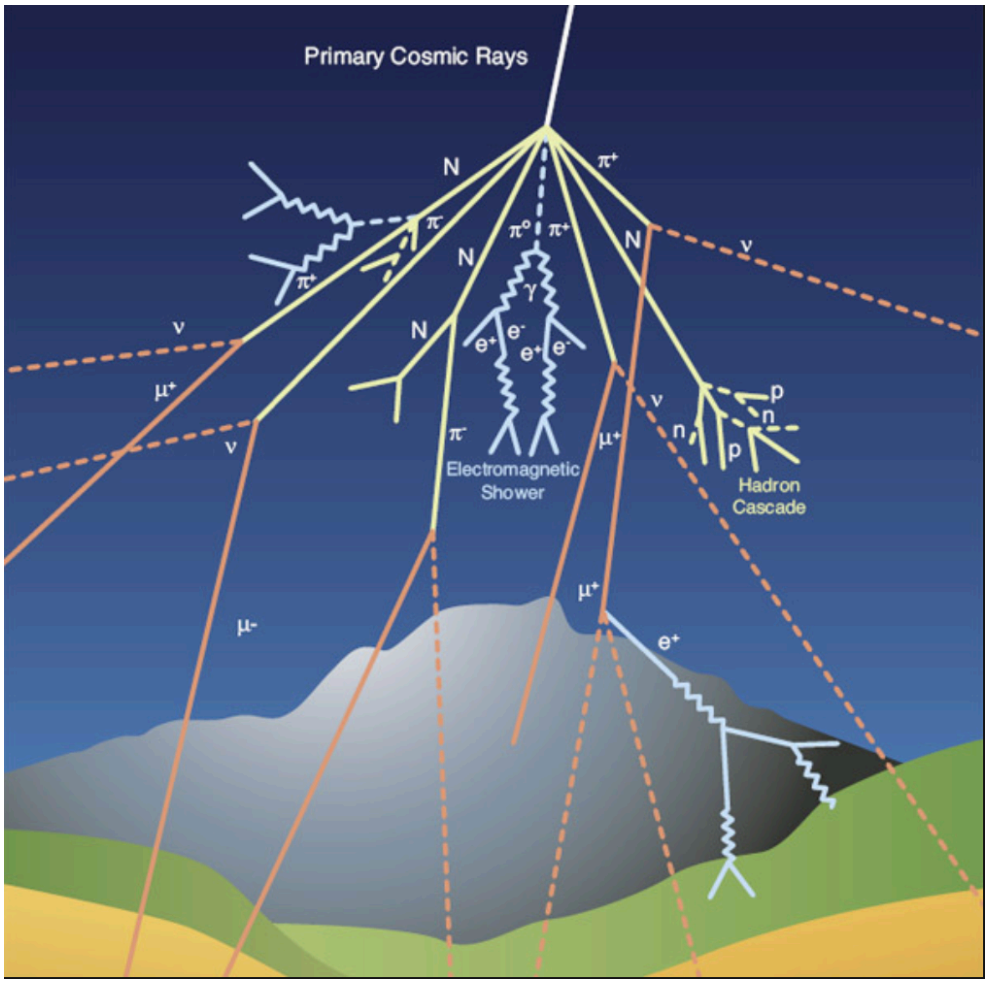
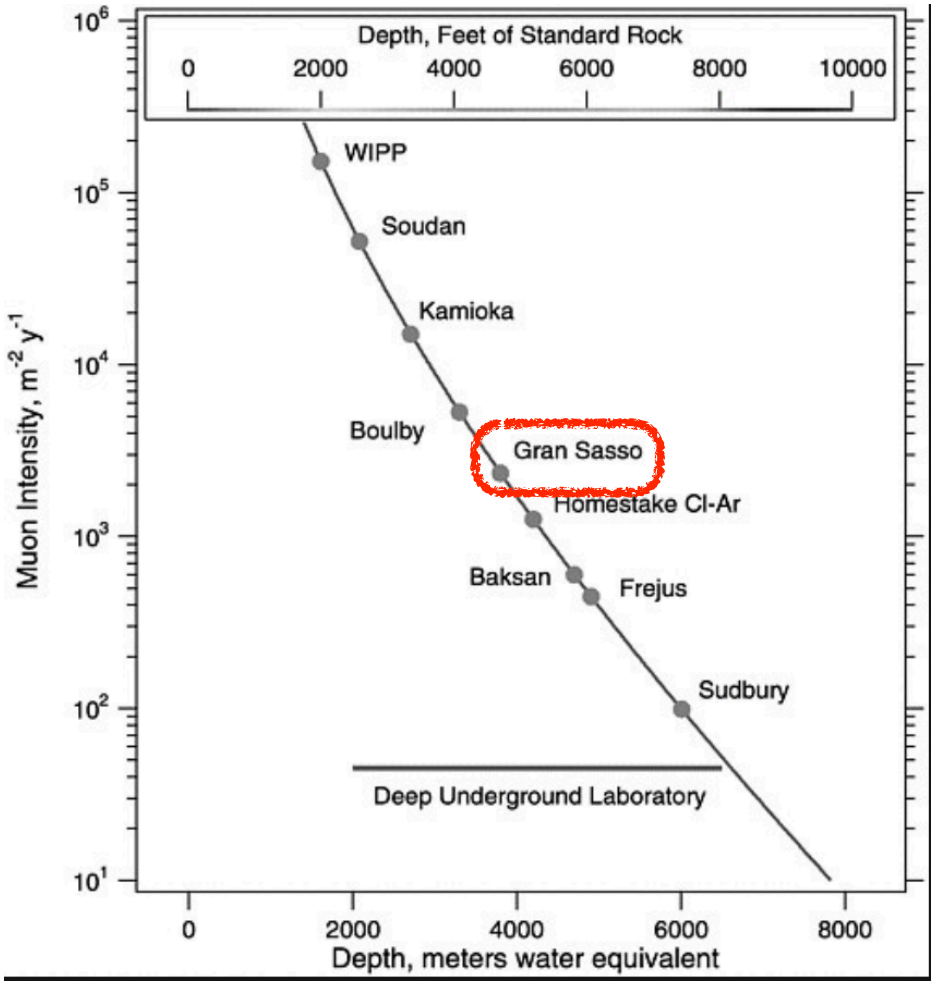
Low Energy Astroparticle Physics at GSSI & LNGS

Elisabetta Baracchini

Gran Sasso Science Institute

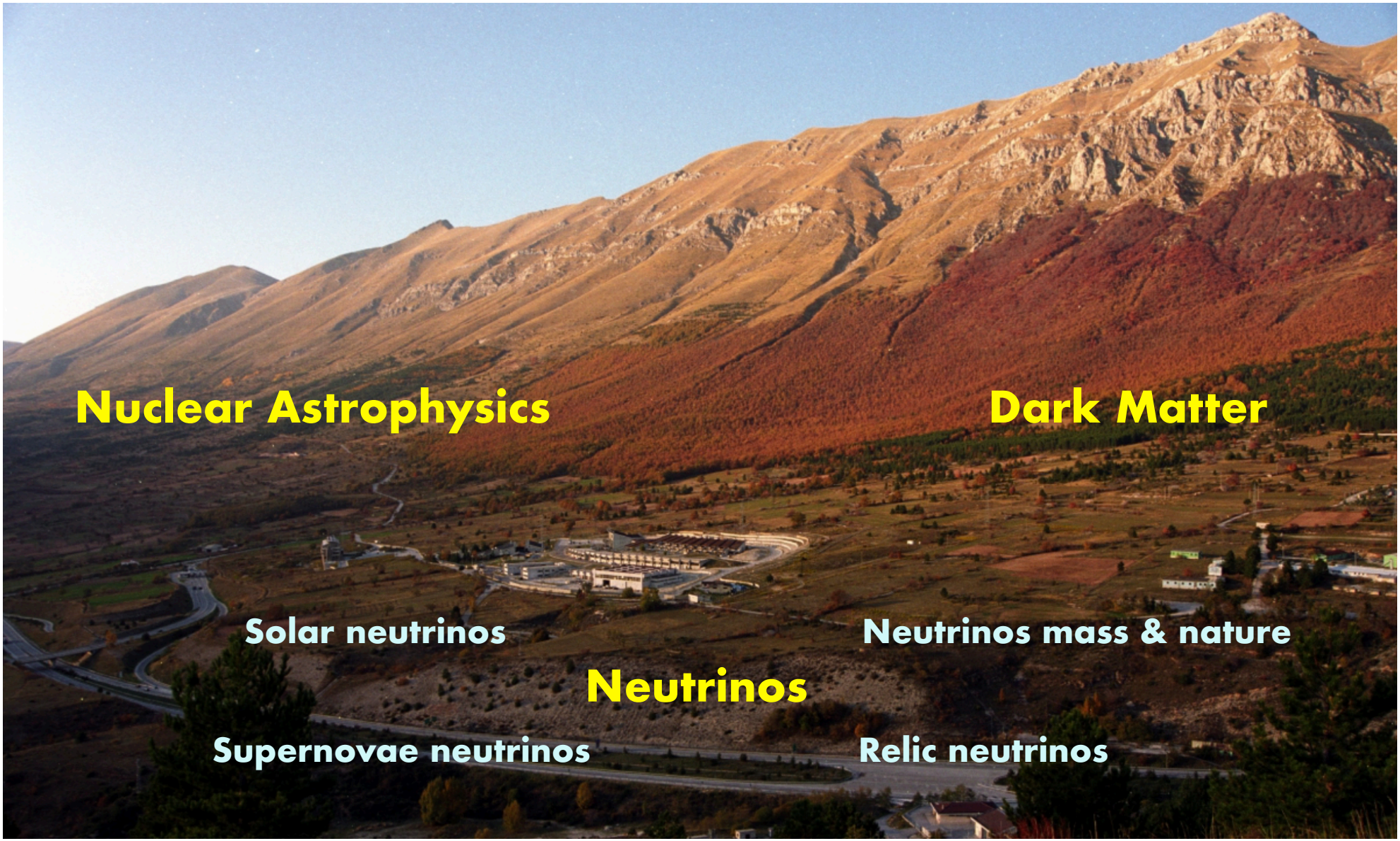
Beneath the mountains



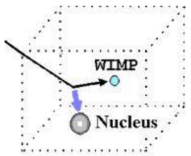


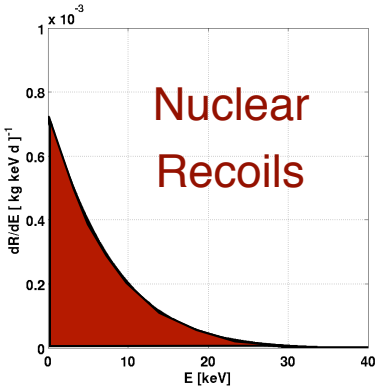
A "quiet place" where to study Universe rarest processes

Exploring the Universe from beneath the mountains



Exploring the Universe from beneath the mountains

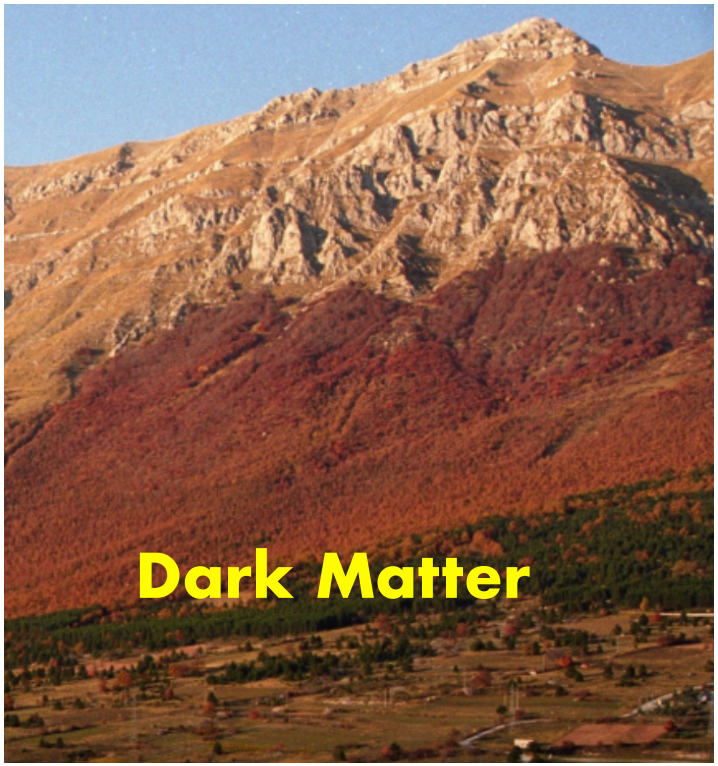




~1 events/kg/year

Mass = 20 GeV

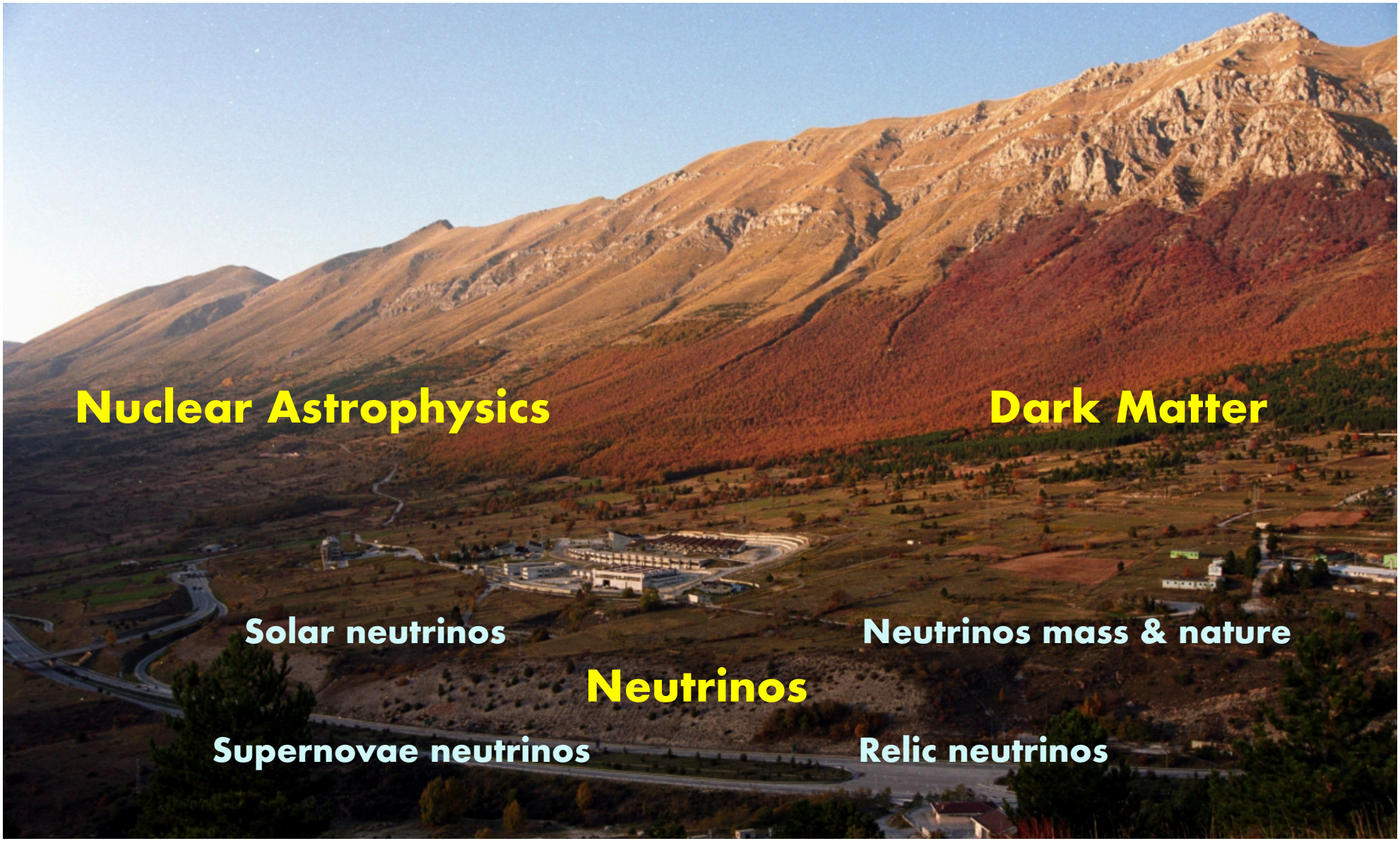
$\sigma_{N,SI} = 10^{-45}$ cm^2



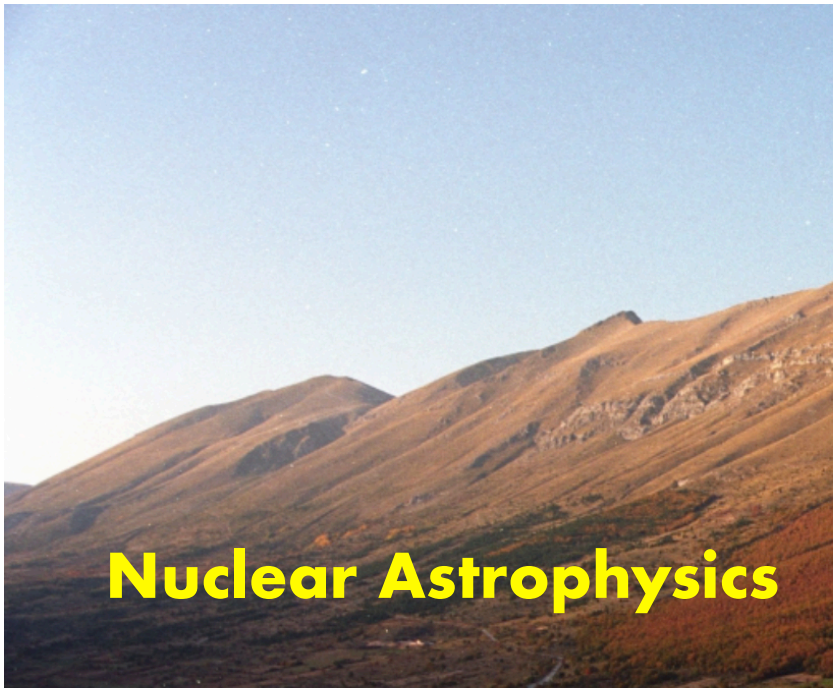
$$\Omega h^2 \simeq \frac{10^{-37}\,\mathrm{cm}^2}{\langle \sigma_{WN} v \rangle} \quad \Rightarrow \quad \sigma_{WN} \sim 10^{-38}\,\mathrm{cm}^2,$$

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

Exploring the Universe from beneath the mountains



Exploring the Universe from beneath the mountains



$$\sigma(E) = \frac{S(E)}{E} \exp\left(-31.29 \cdot Z_1 \cdot Z_2 \cdot \sqrt{\frac{\mu}{E}}\right)$$

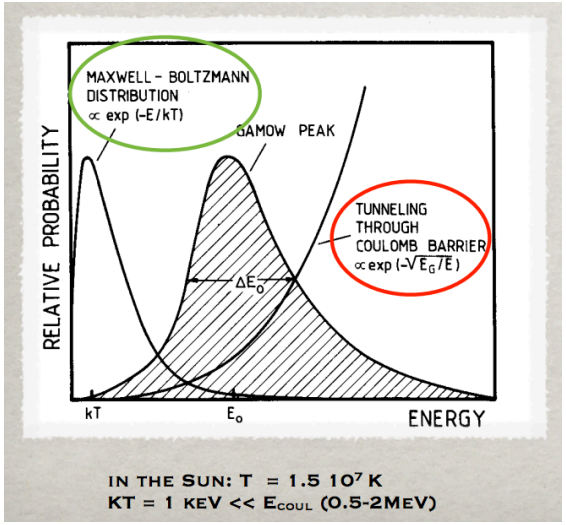
ASTROPHYSICAL FACTOR

GAMOW FACTOR

NUCLEAR REACTIONS THAT GENERATE ENERGY AND SYNTHESIZE ELEMENTS TAKE PLACE INSIDE THE STARS IN A RELATIVELY NARROW ENERGY WINDOW: THE **GAMOW PEAK**

GAMOW ENERGY FOR H-BURNING REACTIONS: FEW TO SEVERAL TENS KEV

PBARN < σ < NBARN

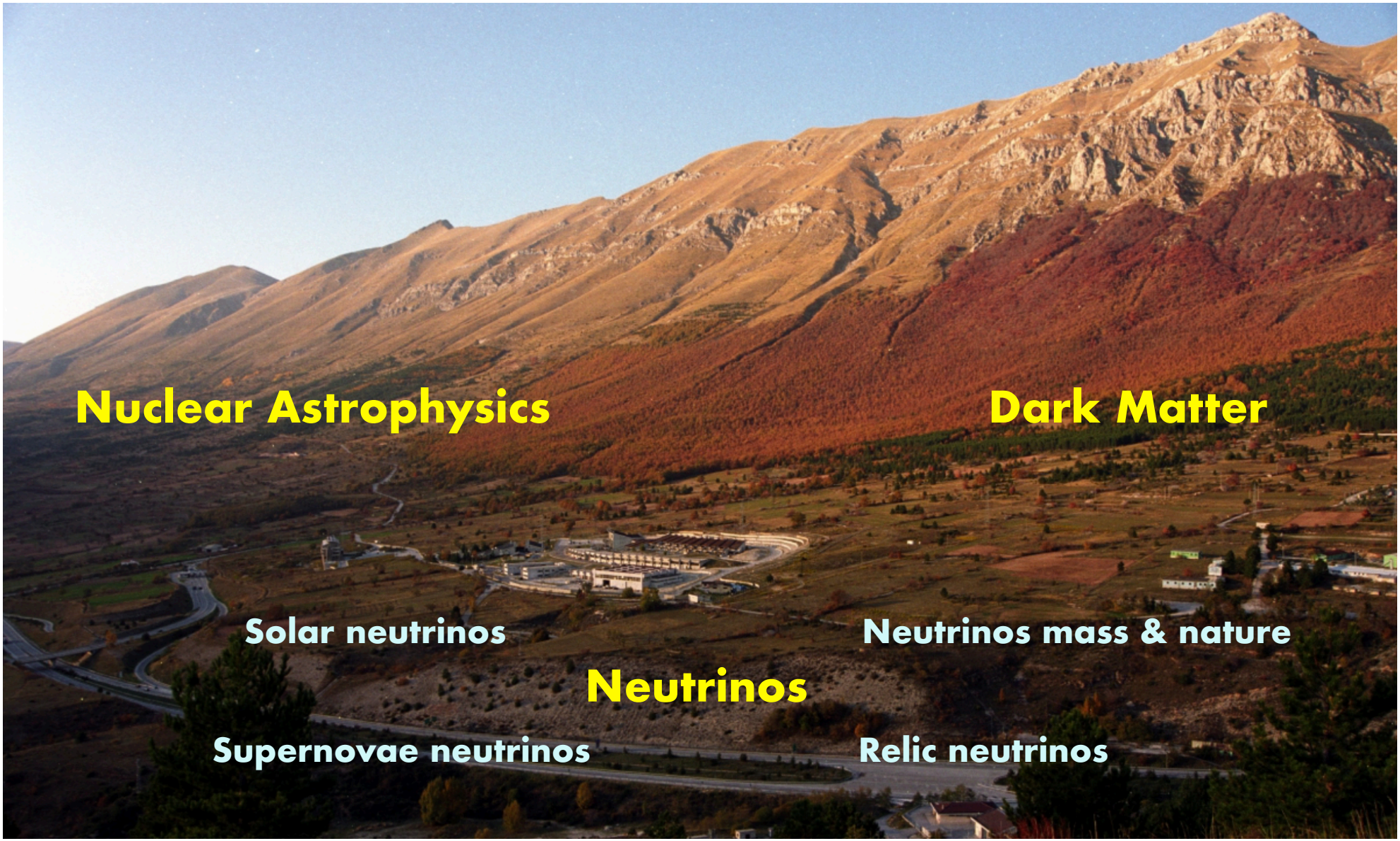


IN THE SUN: T = 1.5 10^7 K
KT = 1 KEV << E_{COUL} (0.5-2MEV)

DIRECT CROSS SECTION MEASUREMENTS FEASIBLE WITH REDUCED COSMIC-RAY INDUCED BACKGROUND

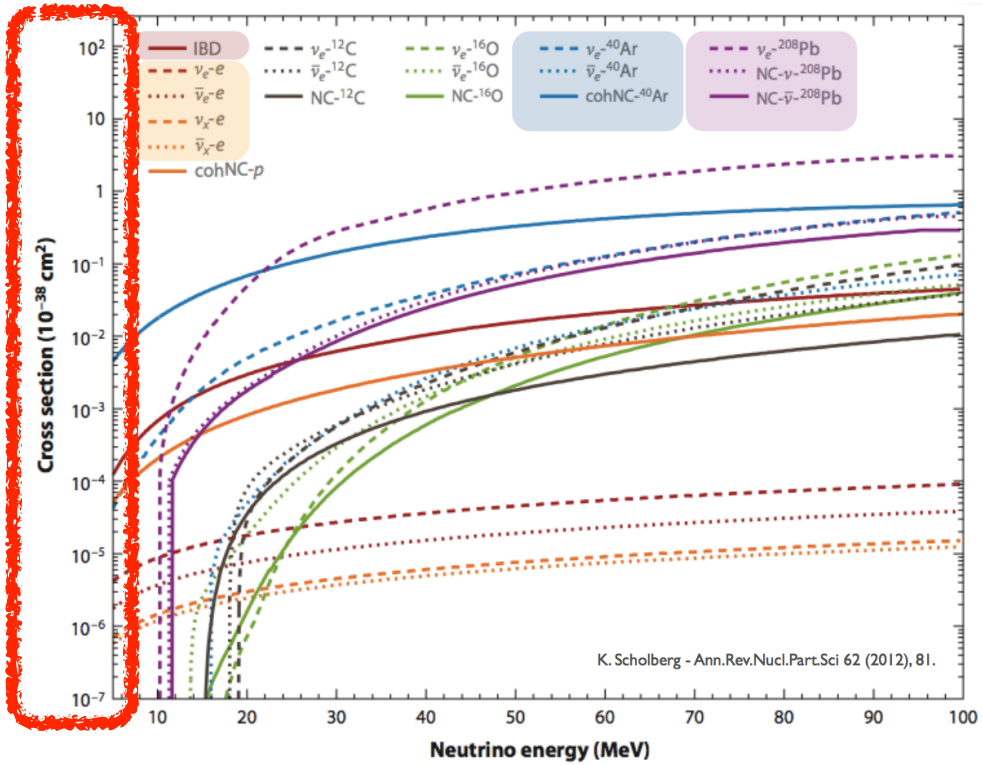
UNDERGROUND MEASUREMENTS

Exploring the Universe from beneath the mountains



Exploring the Universe from beneath the mountains

Neutrino Interactions Cross Section



Neutrinoless double beta decay

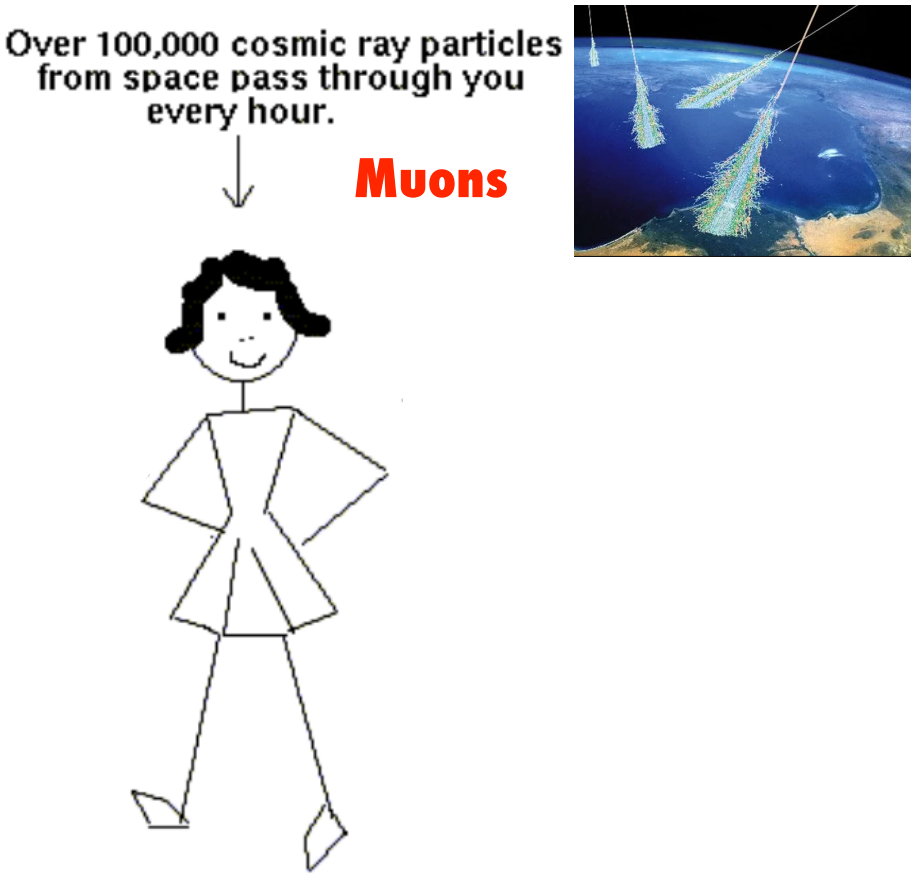
$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{|m_{\beta\beta}|^2}{m_e^2}$$

$$N_{\beta\beta} = ln2 \times N \times t \times \varepsilon \frac{1}{T^{0\nu}_{1/2}}$$

Current limits

$T_{1/2} > [10^{21}\text{-}10^{26}]$ years

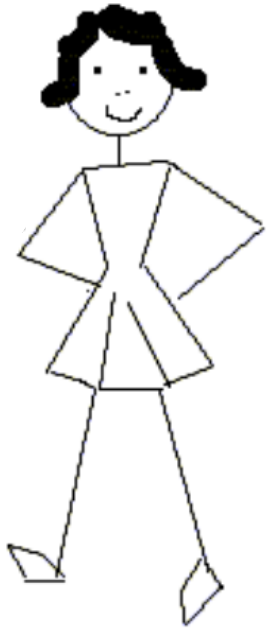
Rare events copycats: not only cosmic rays

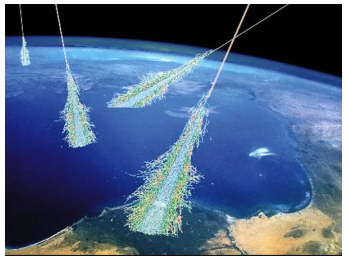


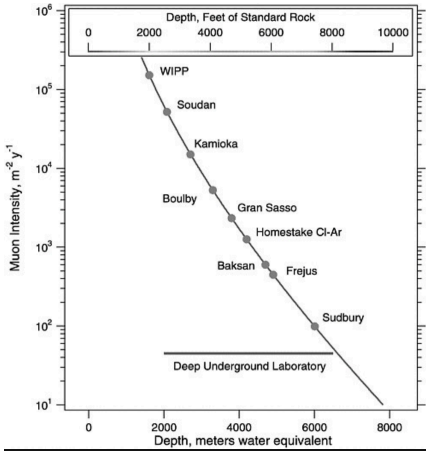
Rare events copycats: not only cosmic rays

Over 100,000 cosmic ray particles from space pass through you every hour.

Muons







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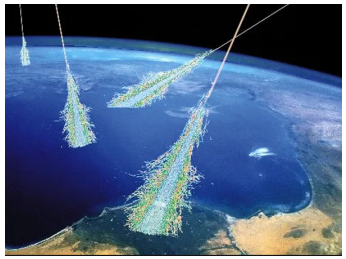

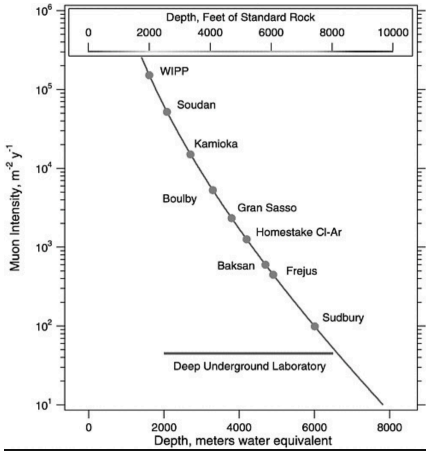

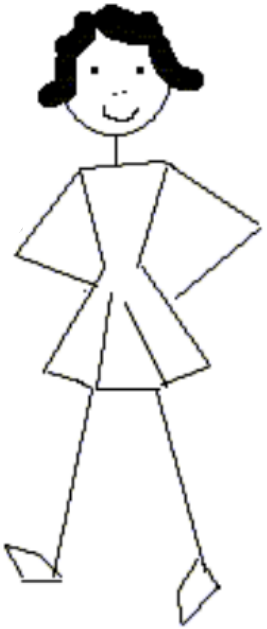

The food you eat contains radioactive atoms. About 15 million potassium atoms decay every hour inside you.

mainly ^{40}K

Rare events copycats: not only cosmic rays

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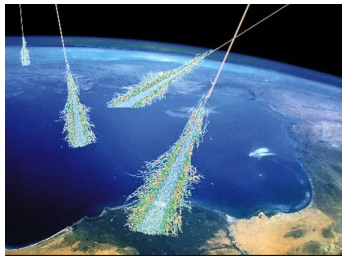
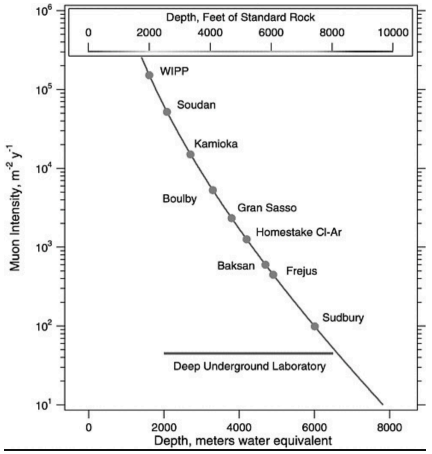
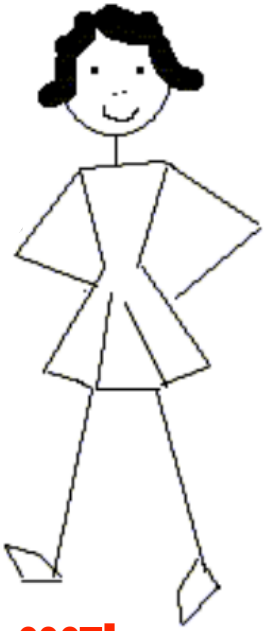
Muons







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mainly ^{40}K

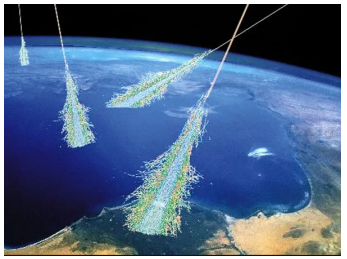
mainly ^{238}U, ^{232}Th

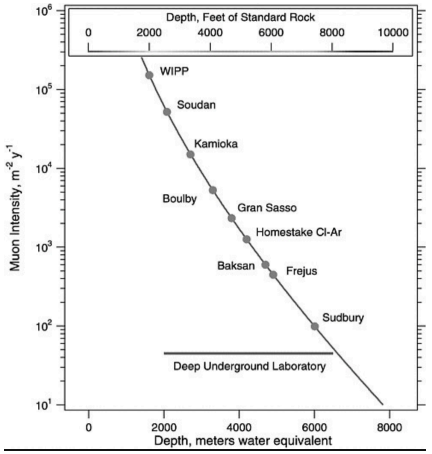
Natural radioactivity in the earth and in building materials sends over 200 million gamma rays through you every hour.

Rare events copycats: not only cosmic rays

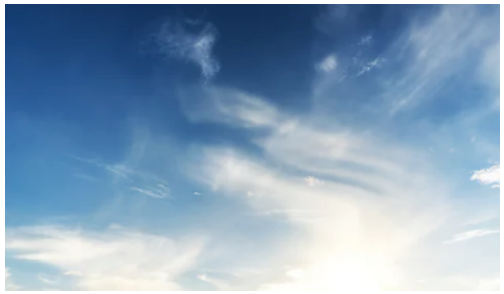
~~Over 100,000 cosmic ray particles from space pass through you every hour.~~

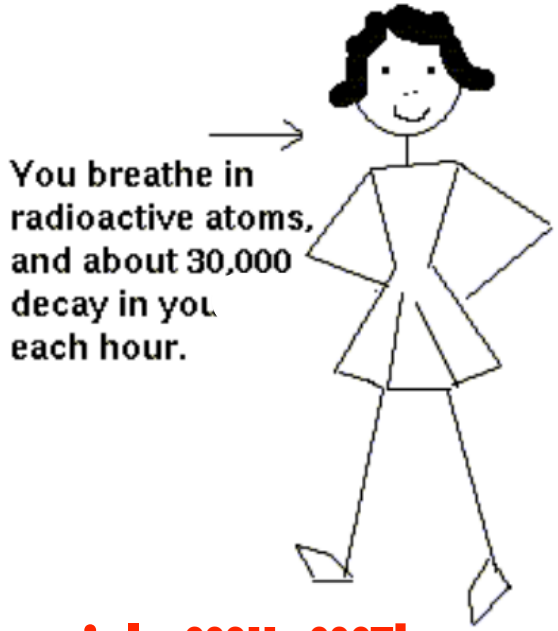
Muons





mainly ^{222}Rn, ^{40}K





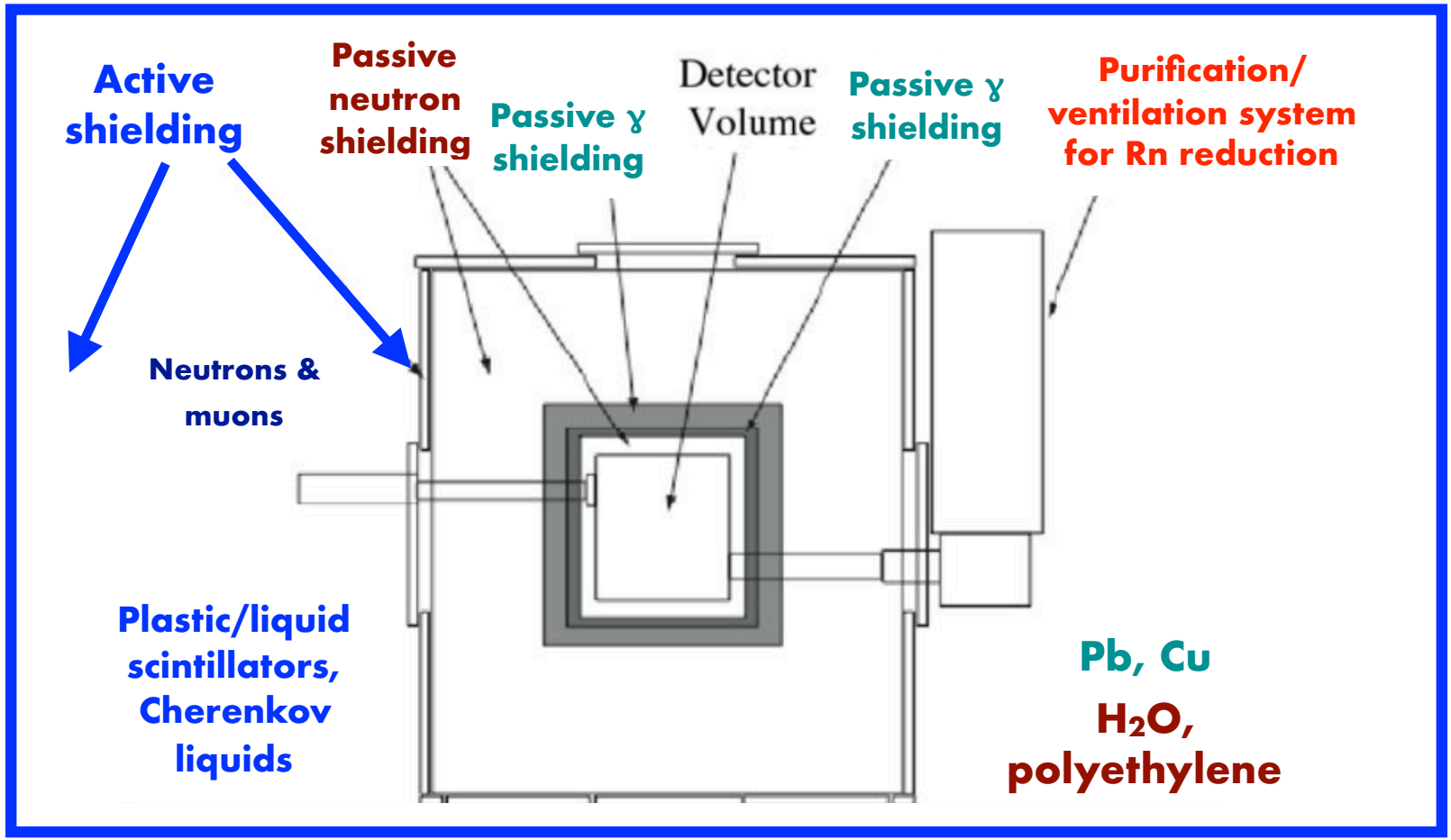
mainly ^{40}K

mainly ^{238}U, ^{232}Th

Natural radioactivity in the earth and in building materials sends over 200 million gamma rays through you every hour.

Additional background suppression

- Ultra-pure Ge spectrometers (as well as other methods) are used to screen the materials before using them in a detector, down to parts-per-billion (ppb) (or lower) levels

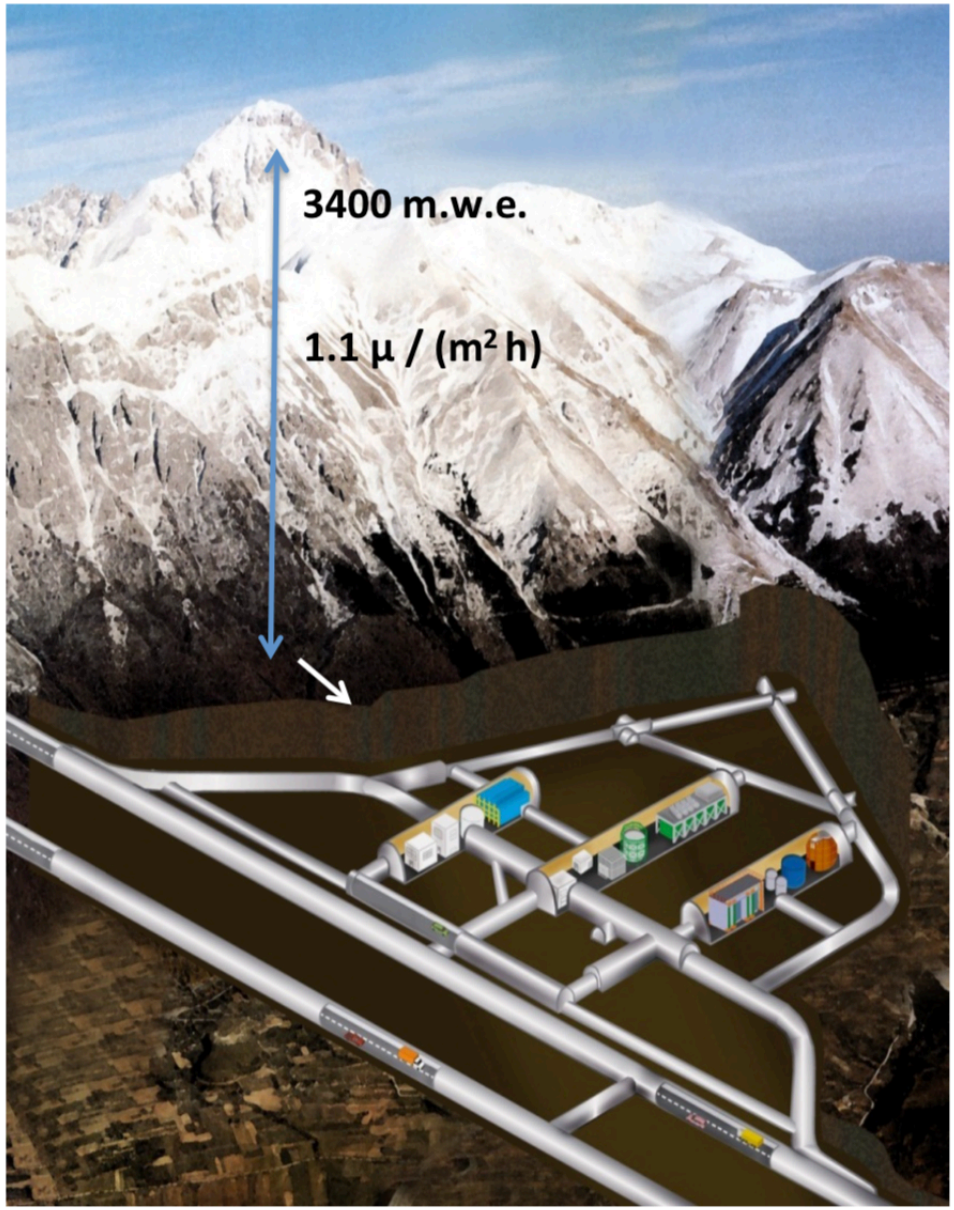


LE-1: Low radioactive background techniques for rare event searches
Ezio Previtali (Università Milano Bicocca and INFN), Lorenzo Pagnanini (INFN)

LE-5: Low Energy Radiation Measurements (LAB)
Matthias Laubenstein (INFN), Lorenzo Pagnanini (INFN), Andrei Puiu (GSSI and INFN)

Laboratori Nazionali del Gran Sasso

- Muon flux: 3.0 10^{-4} $m^{-2}s^{-1}$
- Neutron flux:
  - 2.92 10^{-6} $cm^{-2}s^{-1}$ (0-1 keV)
  - 0.86 10^{-6} $cm^{-2}s^{-1}$ (> 1 keV)
- Rn in air: 20-80 Bq m^{-3}
- **Surface: 17 800 m^2**
- **Volume: 180 000 m^3**
- Ventilation: 1 vol / 3.5 hours
- **Mechanical Design and Workshop**
- **Electronics Lab & Service**
- **Chemistry Lab & Service**
- **ULB Lab & Service**
- > 900 users from 29 countries
- ~ 100 Staff
- 225 avg. daily presence in 2014
- ~ 8000 visitors/y
- Virtual tour via Street View

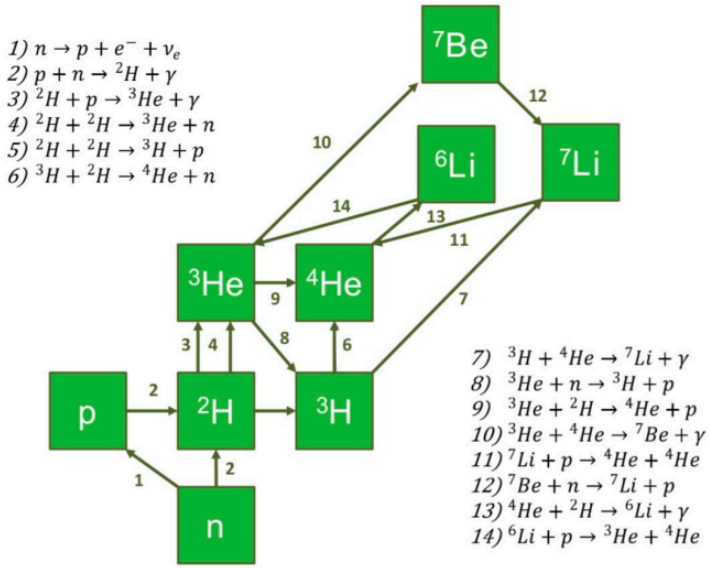


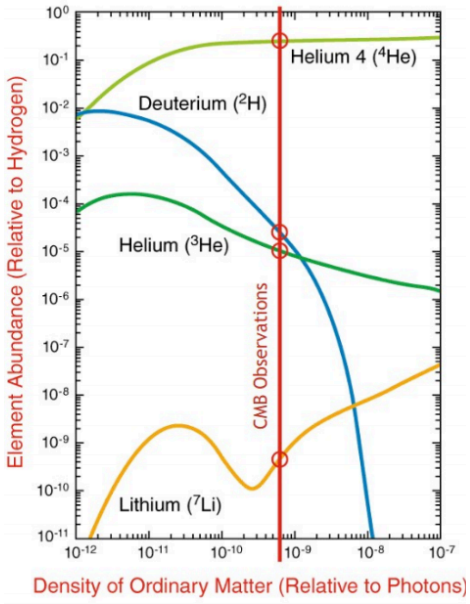
D. Piatti

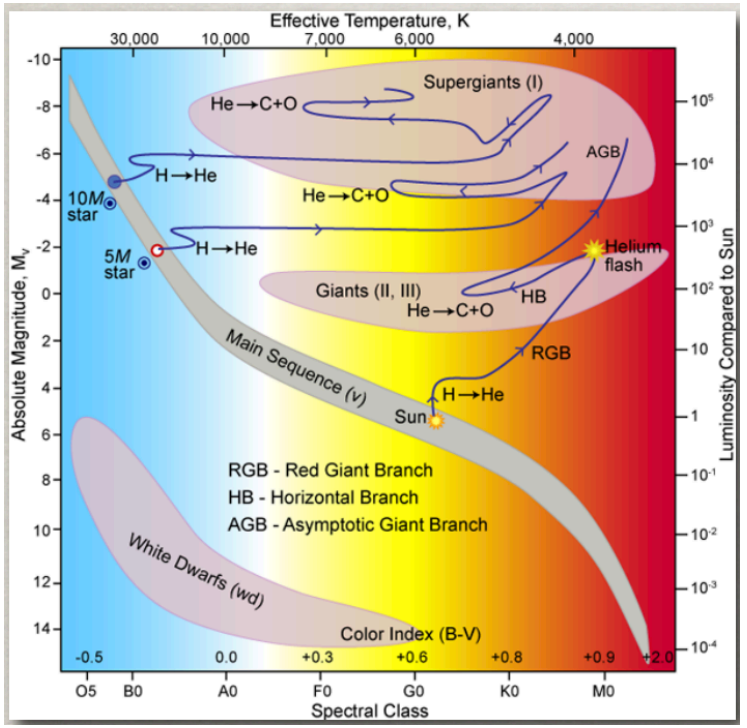
Nuclear Astrophysics

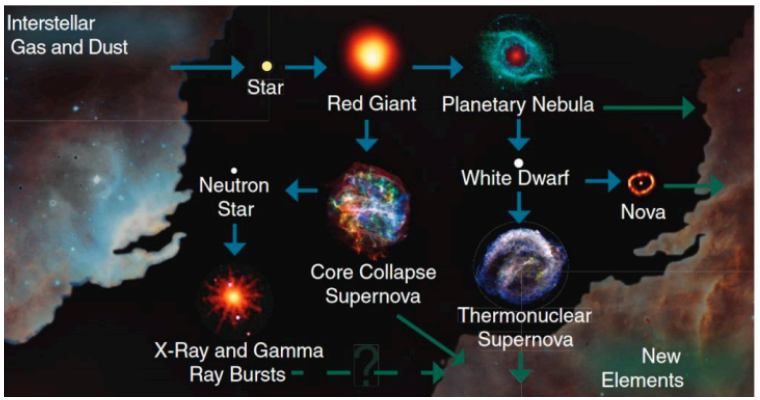
Nuclear Astrophysics

- Study of the nuclear reactions that shape much of the visible Universe
  - Sun, Supernovae, stellar evolution
  - Study of Big Bang Nucleosynthesis



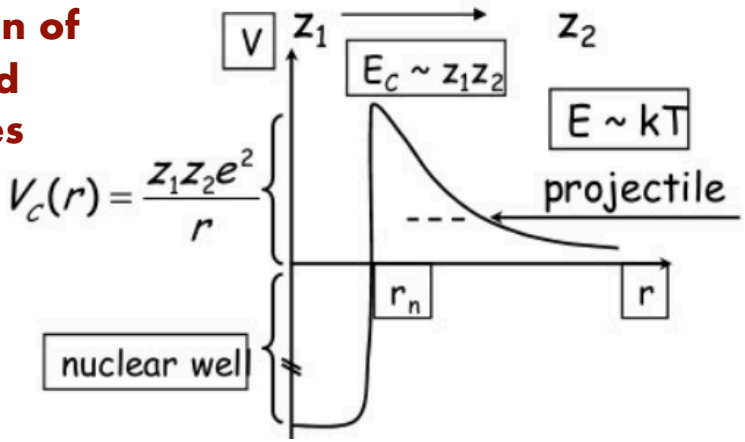




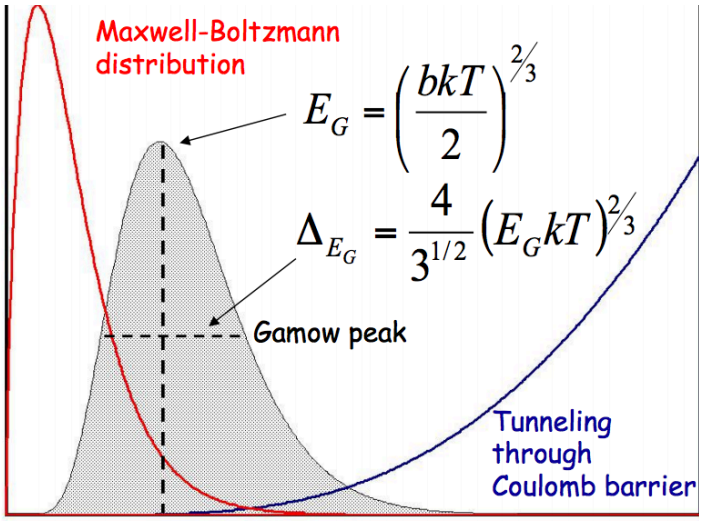


Reaction rate & Gamow peak

Reaction of charged particles



TUNNEL EFFECT!



Nuclear Effects **Coulomb barrier**

Reaction cross section

$$\sigma(E) = \frac{S(E)}{E}\exp(-2\pi\eta) \qquad \eta = \frac{Z_1 Z_2 e^2}{\hbar v}$$

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \frac{S(E)}{E}\exp\left[-\frac{b}{E^{1/2}}\right] E\exp\left[-\frac{E}{kT}\right] dE$$

Yield ~ 0.3-30 counts/year

DIRECT CROSS SECTION MEASUREMENTS FEASIBLE WITH REDUCED COSMIC-RAY INDUCED BACKGROUND

UNDERGROUND MEASUREMENTS

The reaction rate is given by the convolution of the cross section with the Maxwell-Bolzmann energy distribution of colliding nuclei = Gamow peak

- Sun:
  - kT ~ 1 keV (T ~ 1.5×10^7 K)
  - E_c ~ 0.5 - 2 MeV (Coulomb barrier)
  - E_0 ~ 5 - 30 keV (Gamow peak) for reactions of H burning
  - kT << E_c → Tunnel effect
  - Cross sections in the range of pb-fb at stellar energies → with typical laboratory conditions reaction rate R can be as low as few events per month..

z_1=p and z_2=p (e.g. in the Sun)

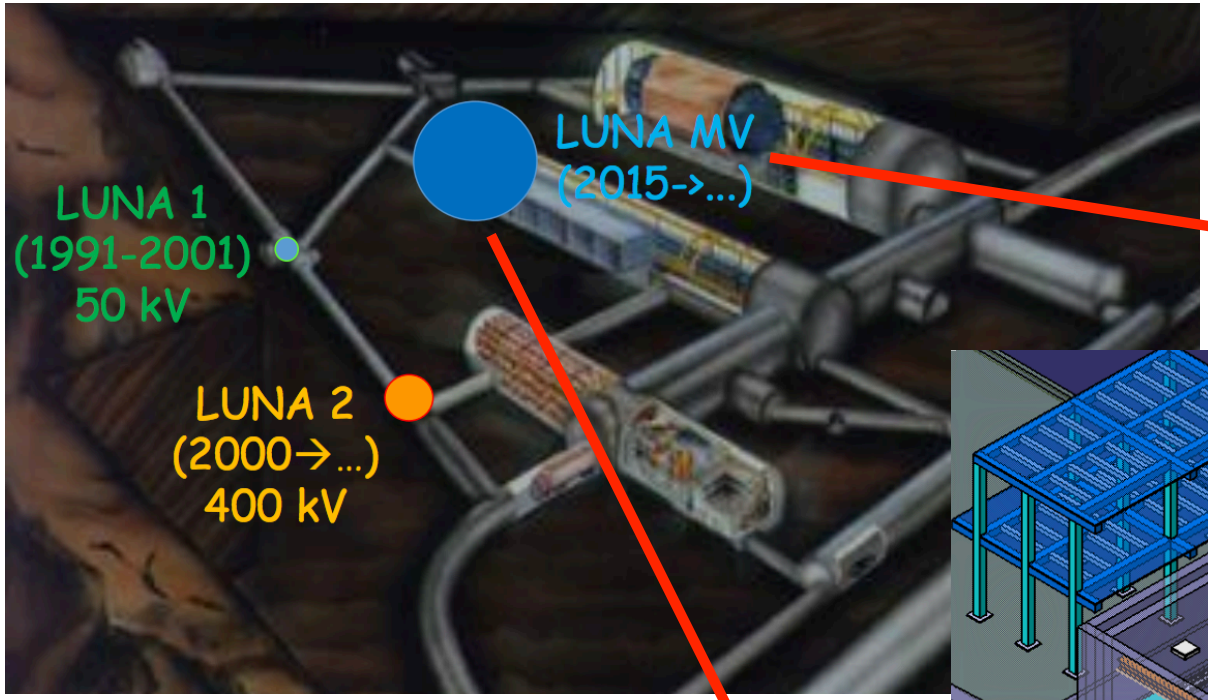
T ~ 15×10^6 K⇒E = kT ~ 1 keV

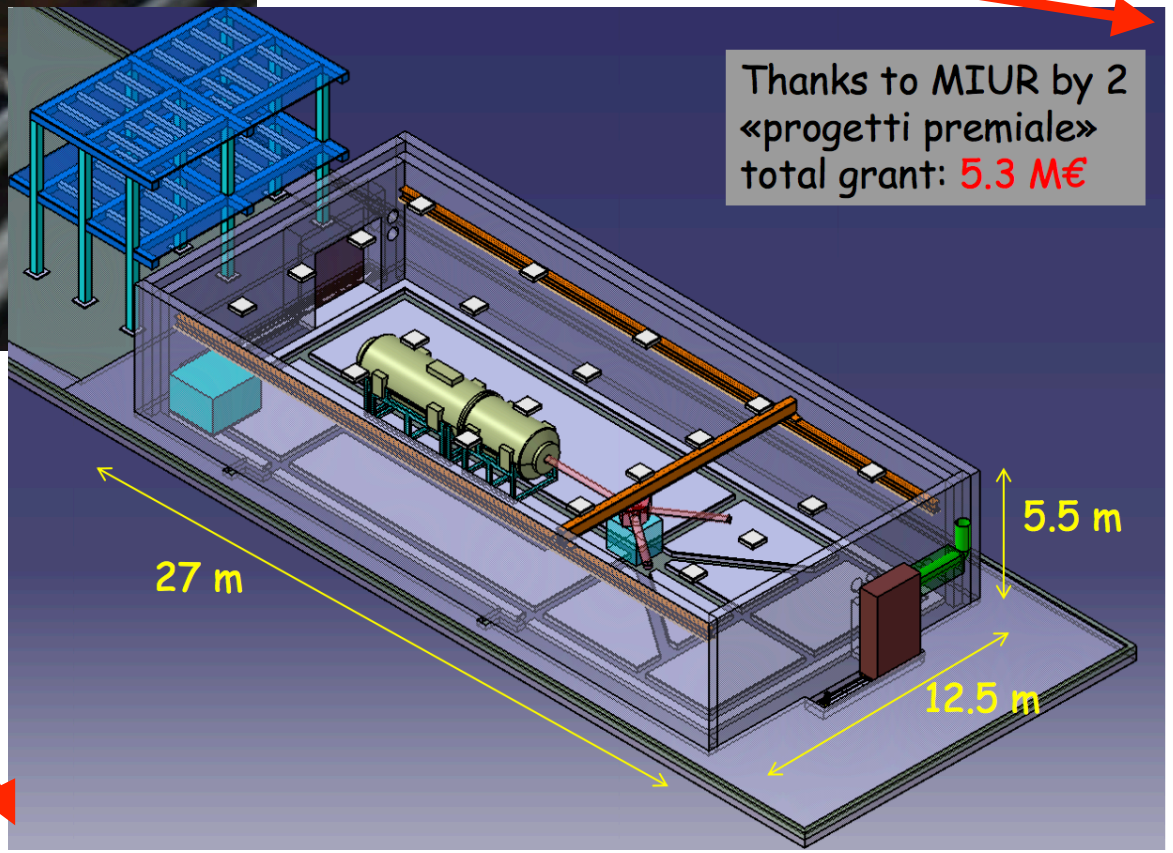
E_c = 550 keV

during quiescent burnings:

kT << E_c

Laboratory for Underground Nuclear Astrophysics: LUNA

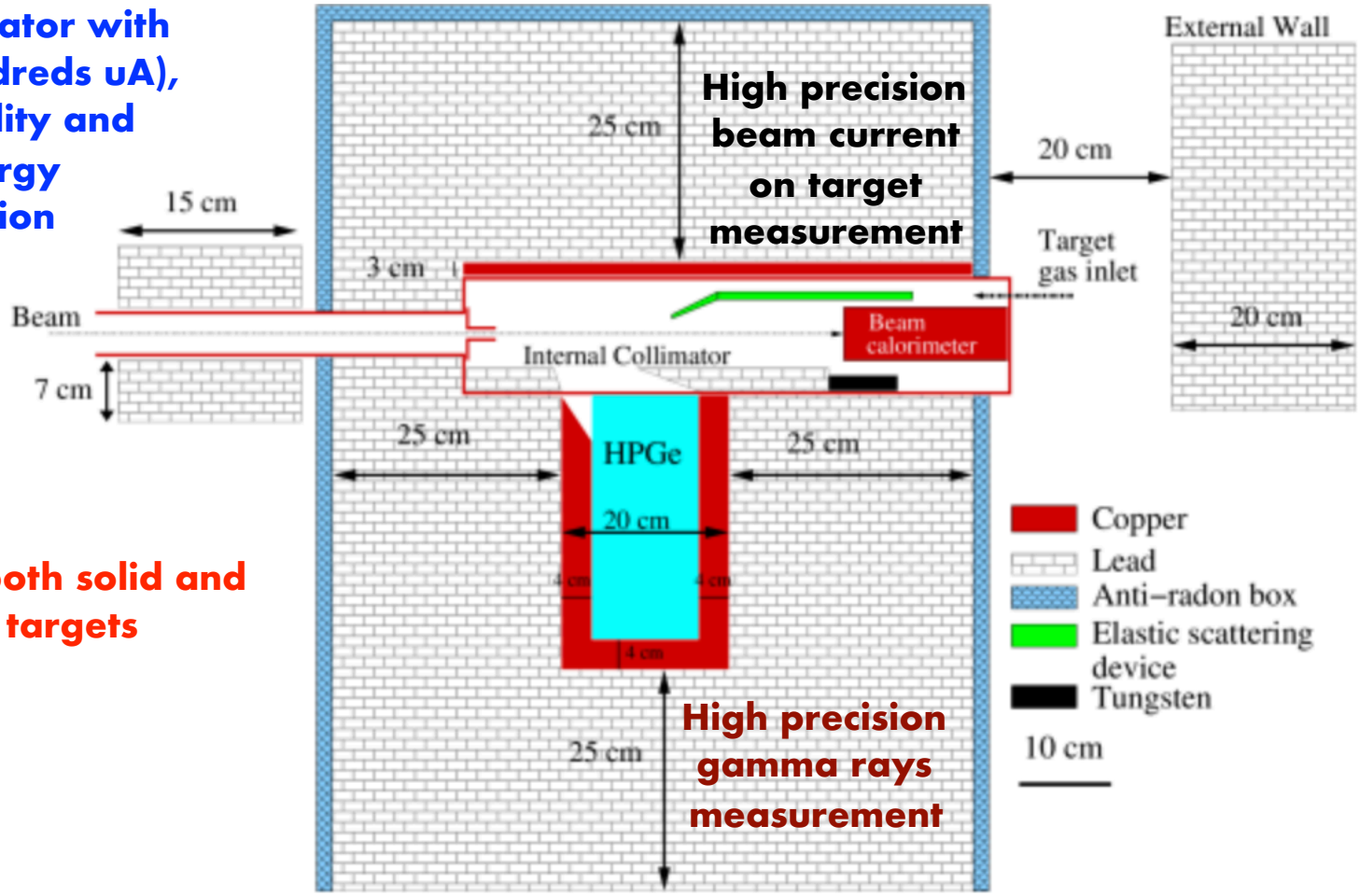




LUNA experimental setup

Ion beam accelerator with high current (hundreds uA), long term stability and precise energy determination

Possibility of both solid and gaseous targets



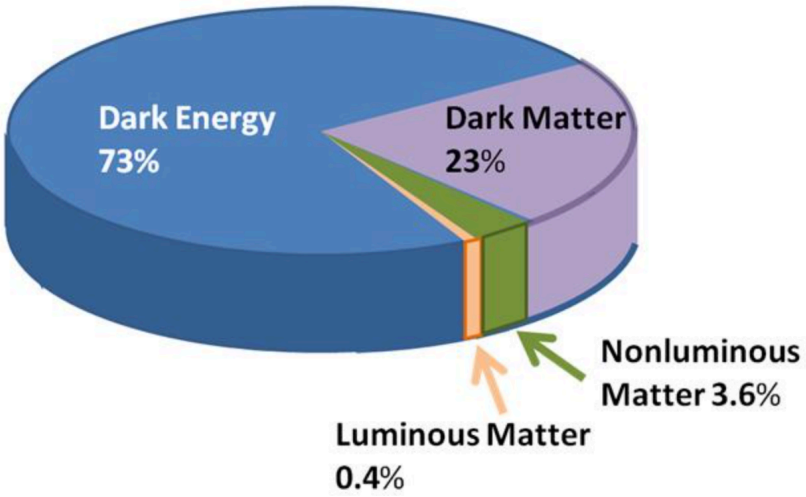
Possibility of different detection setup by combining: HpGe (high resolution), BGO (high efficiency) ^{3}He counters..

Direct Dark Matter searches

It's a Dark Universe

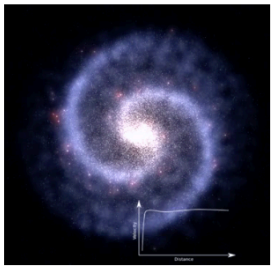
LE-TH2	P. Ullio

Universe composition

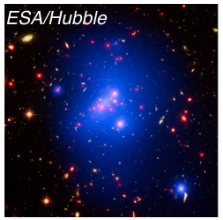


"Dark" Matter because it does not interact with light

Galaxy rotation curves



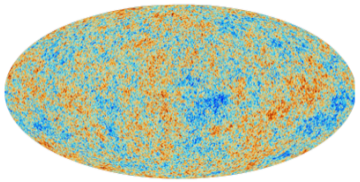
Galaxies motion inside clusters



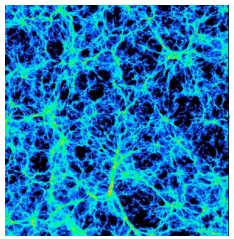
Galactic Collisions

...and many more

Cosmic Microwave Background



Large scale structures

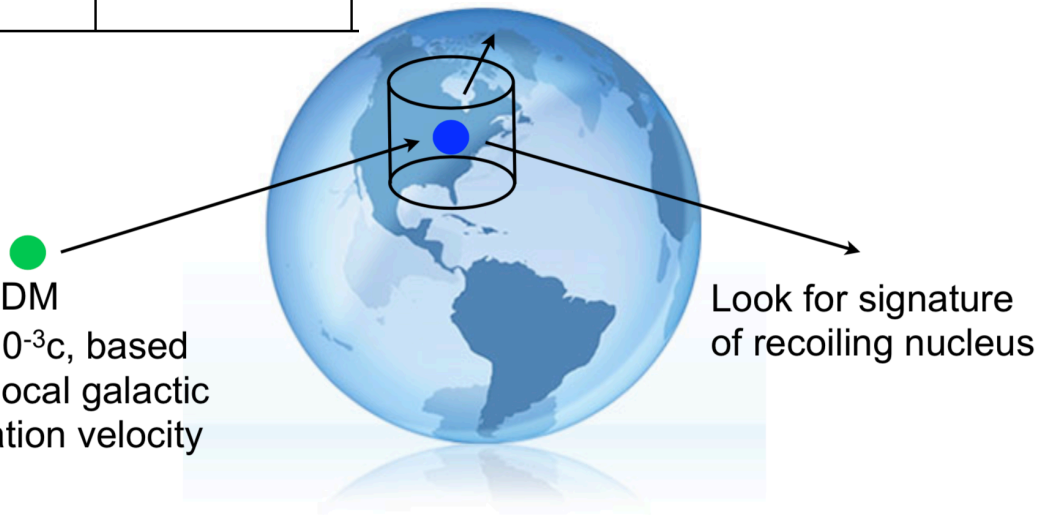


Larger scales explored, older times probed

Dark Matter gravitational evidences

Direct Dark Matter detection principle

LE-EXP2	E. BARACCHINI



REVIEW D VOLUME 31, NUMBER 12

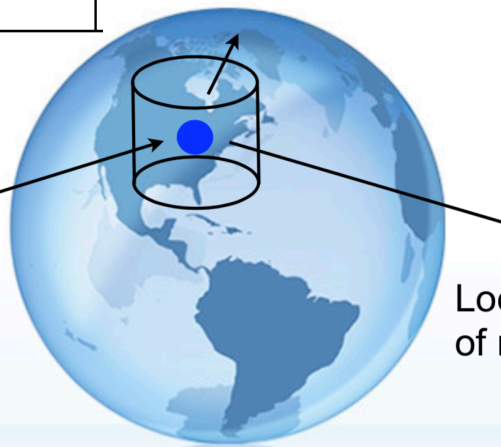
Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

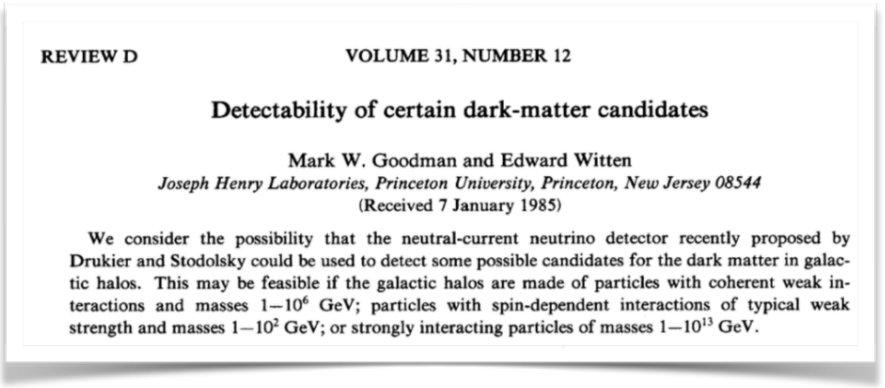
Direct Dark Matter detection principle

LE-EXP2	E. BARACCHINI



DM
v~10^{-3}c, based on local galactic rotation velocity

Look for signature of recoiling nucleus



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(Received 7 January 1985)

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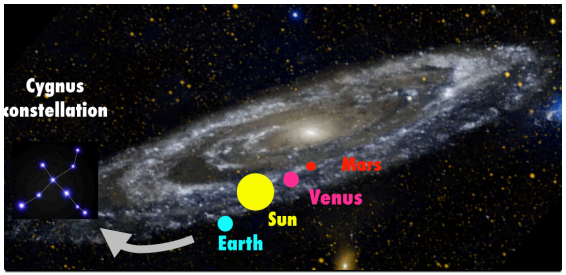
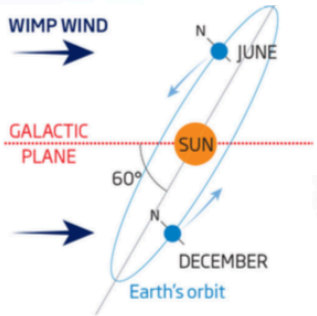
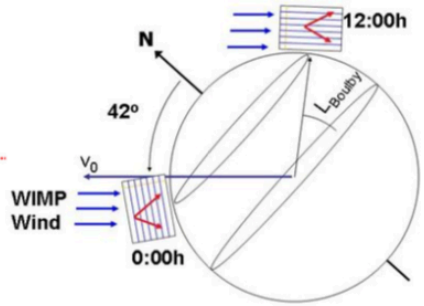


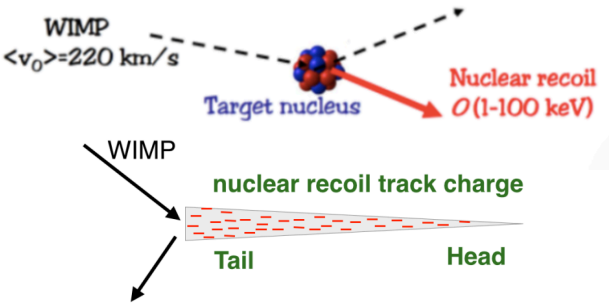
Our Galaxy



Solar system



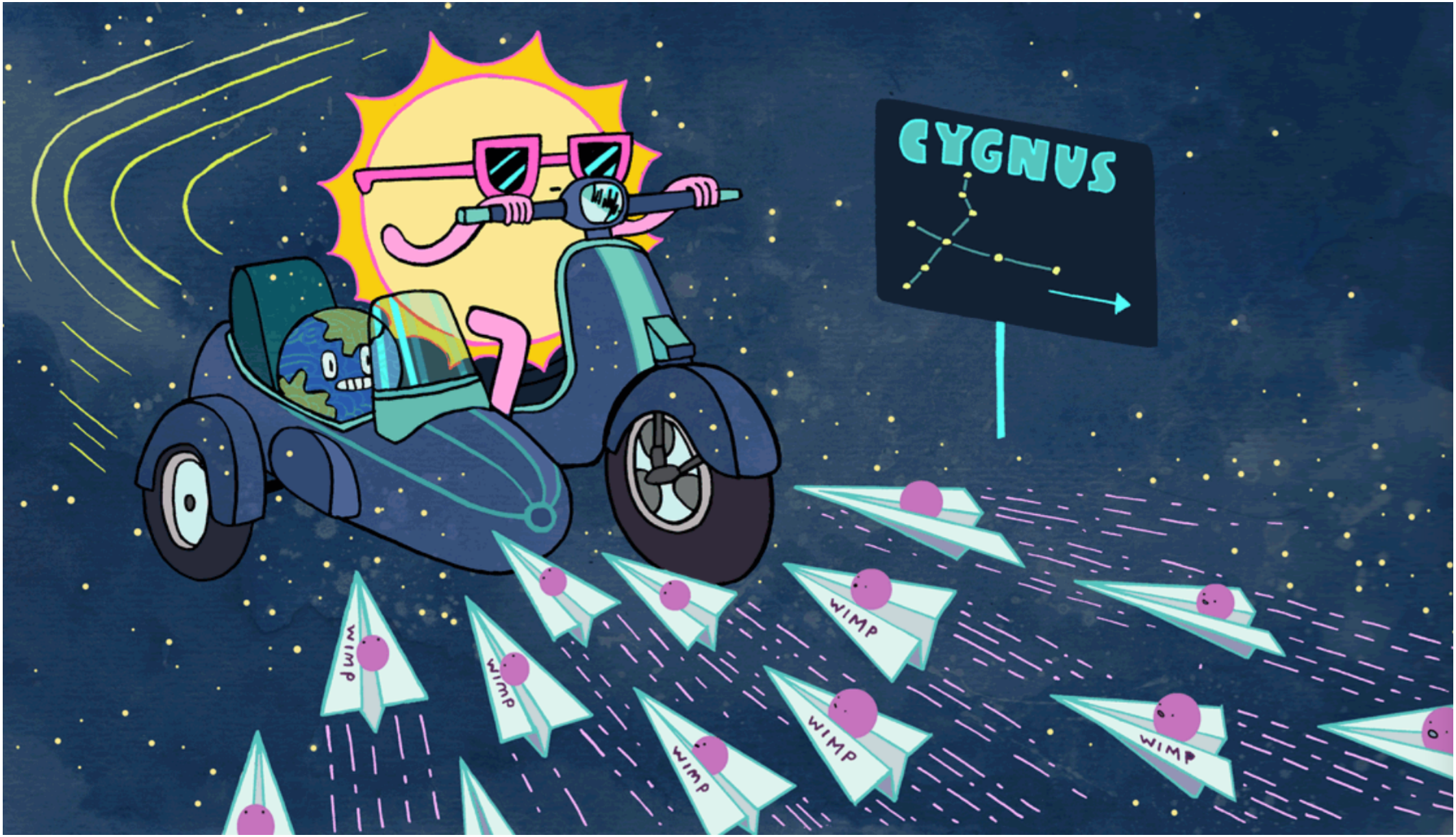
Earth



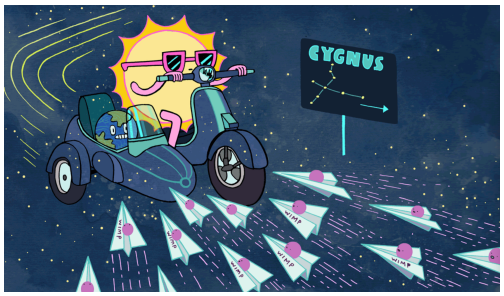
Detector target

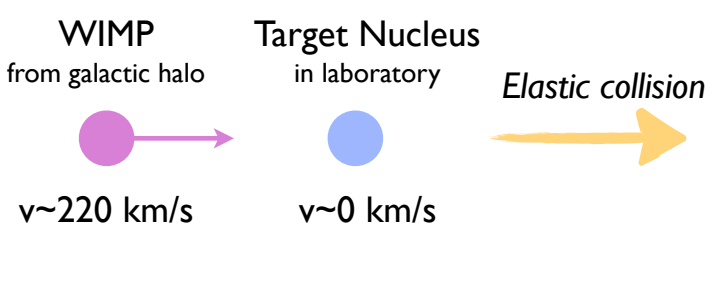
Look at a larger number of nuclei (...electrons...) and see if any of them recoils due to a hit-and-run collision with a WIMP.

Driving to CYGNUS with a DM wind blowing in your hair...



Direct DM searches facts & figures

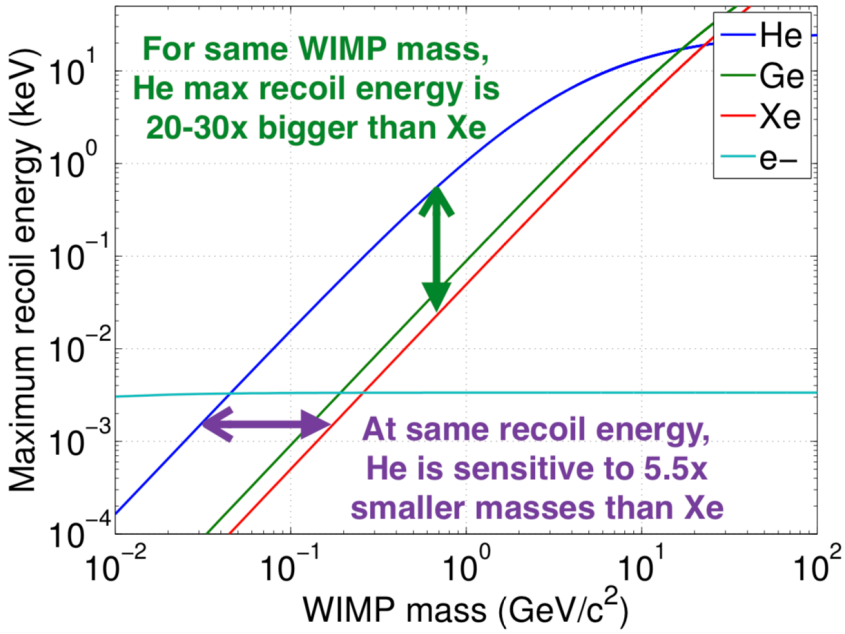




Recoiling nuclei (partially) retain WIMP direction

$$E_R = \frac{p^2}{2m_N} = \frac{m_r^2 v^2}{m_N}(1 - \cos\theta)$$

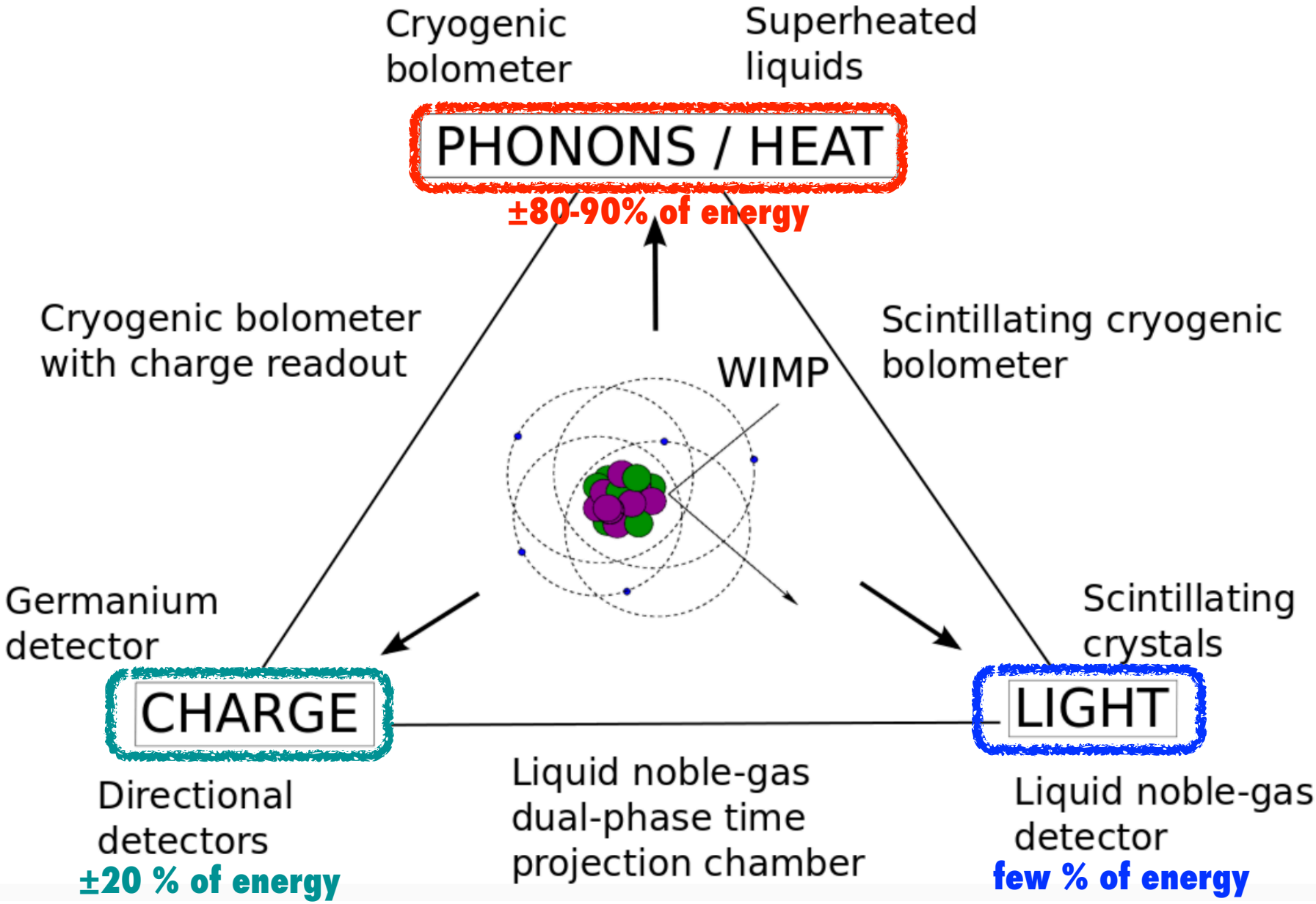
Sensitivity to different WIMP masses depends on energy threshold AND target nuclei



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

Interaction rate & nuclear recoil energy are very low

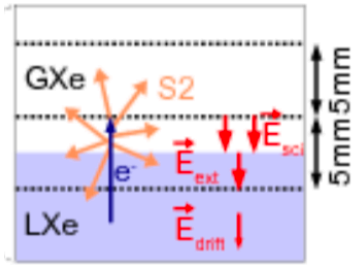
Direct DM searches experimental techniques



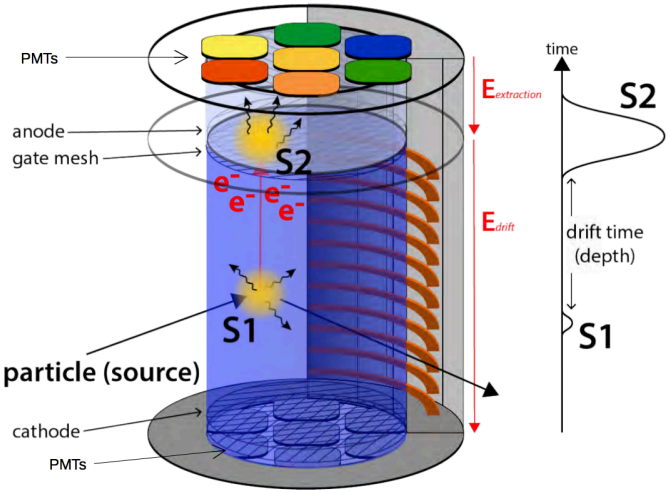
C. Ferrari S. Horikawa

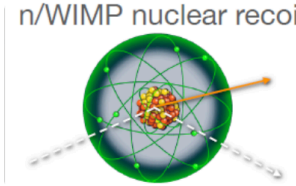
XenonNT & Darkside-20k

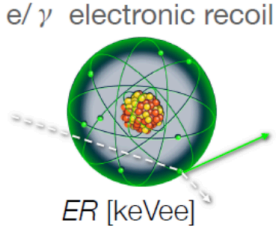
Z fiducialization: S_1-S_2 time difference
X-Y fiducialization: PMTs pattern

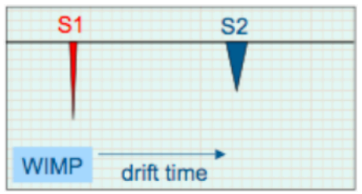


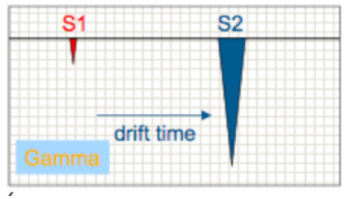
S_2 amplification via electroluminescence

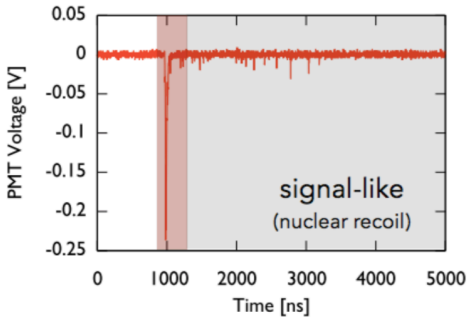


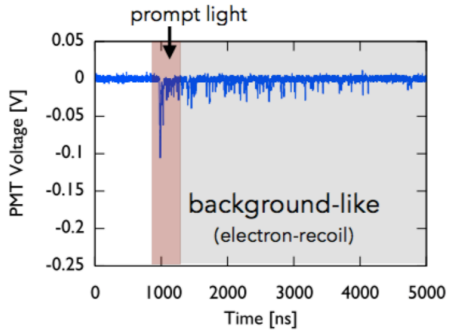












LE-3: Rare event searches with noble liquid TPC
Elena Aprile (Columbia University)

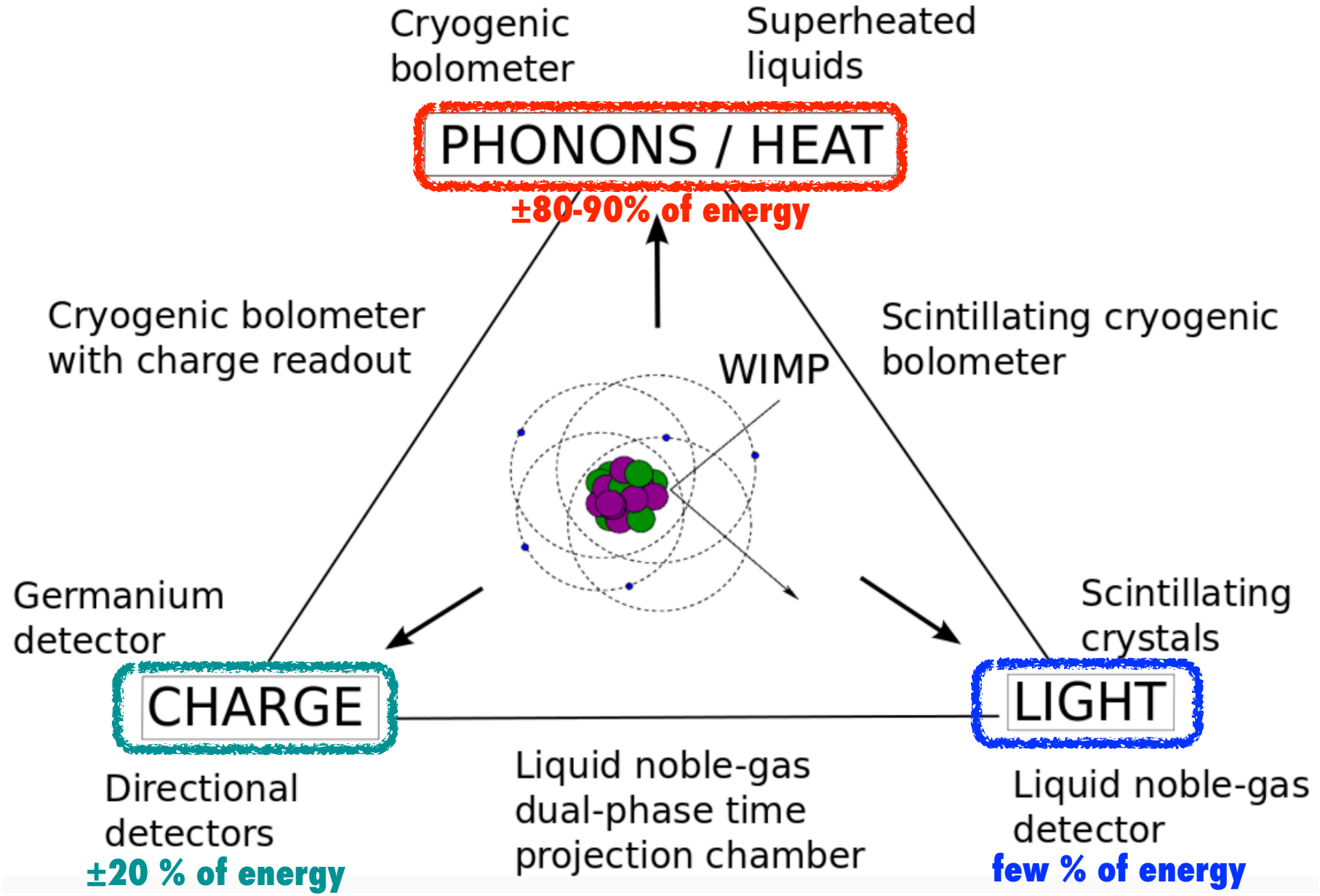
LE-8: Cryogenics sensors and related electronics
Andrei Puiu (GSSI and INFN), Marcello Messina (INFN LNGS)

ER/NR discrimination via S_1/S_2 comparison + PSD (for LAr)

CHARGE — LIGHT

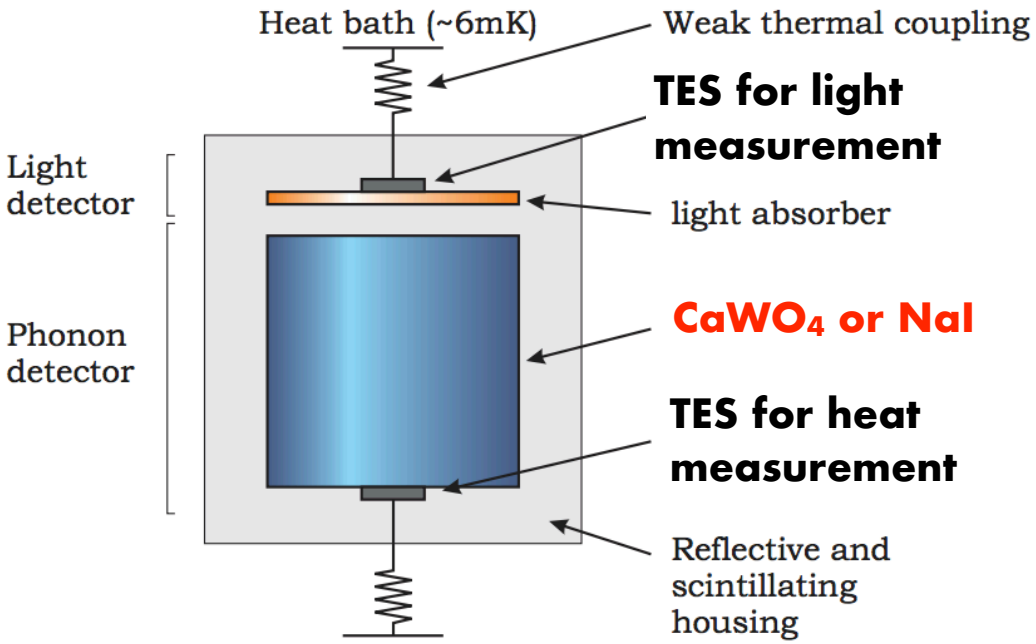
Liquid noble-gas
dual-phase time
projection chamber

Direct DM searches experimental techniques

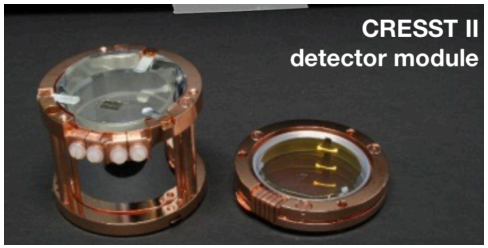


M. Olmi N. Di Marco

CRESST & COSINUS

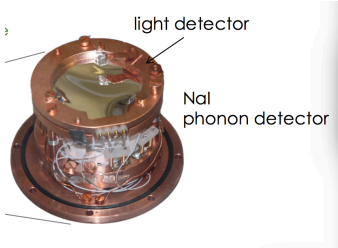


CRESST



$CaWO_4$

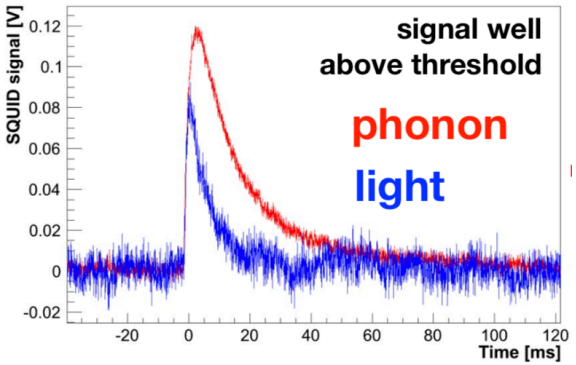
COSINUS

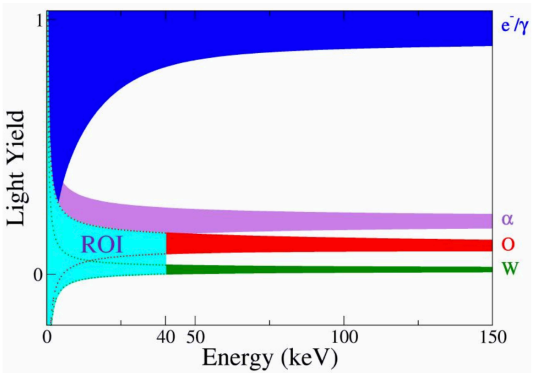


NaI

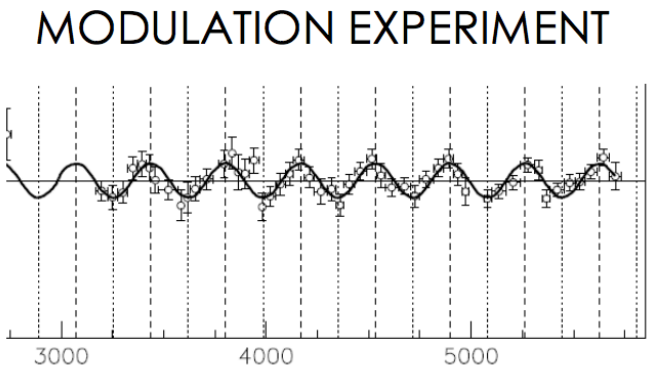
Scintillating cryogenic bolometer

ER/NR discrimination via energy (i.e. heat) vs light comparison



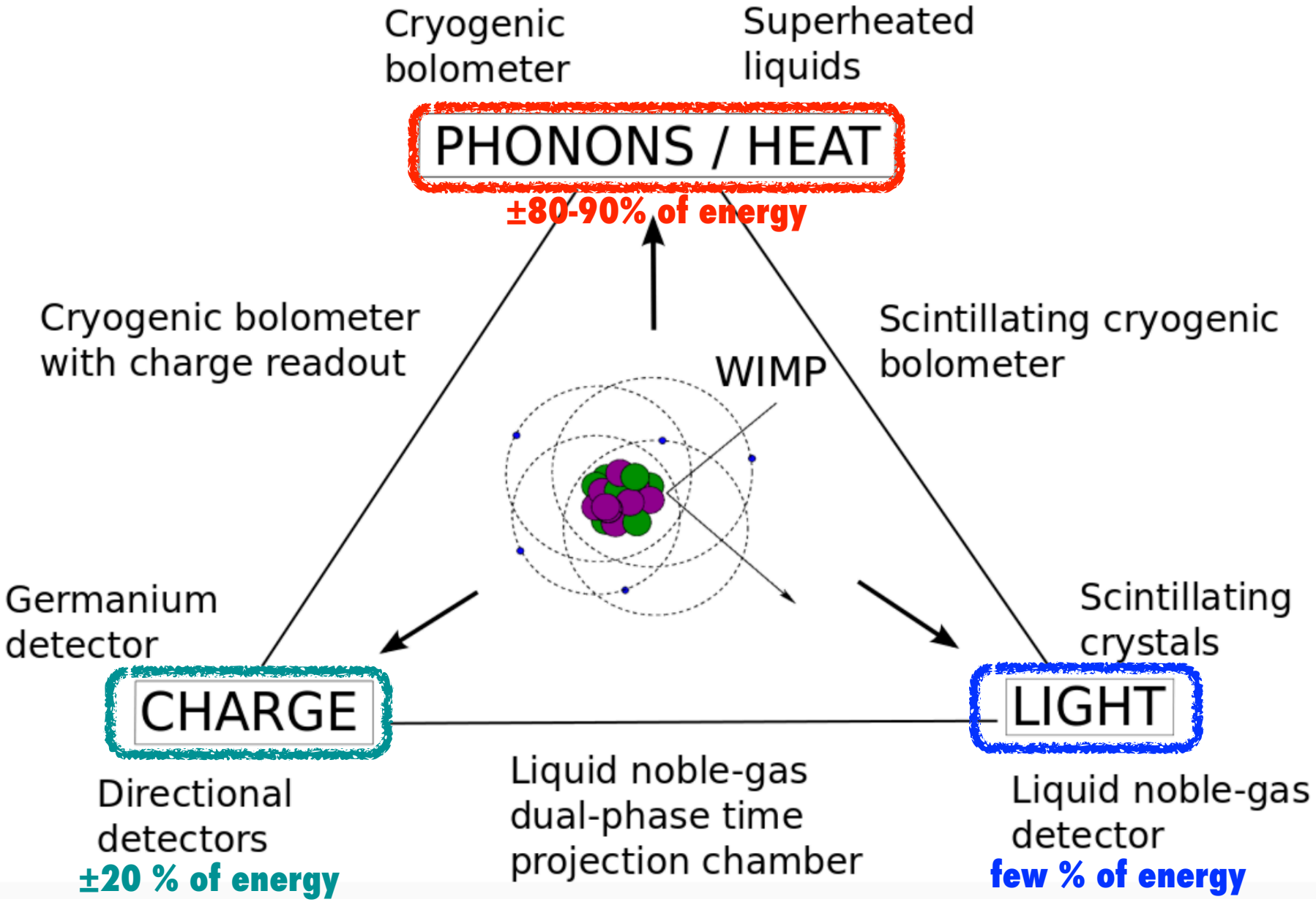


COSINUS to test DAMA via modulation + ER/NR discrimination



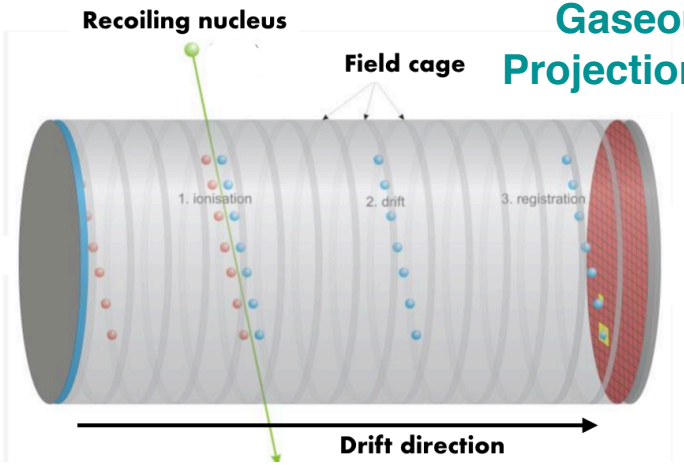
LE-8: Cryogenics sensors and related electronics
Andrei Puiu (GSSI and INFN), Marcello Messina (INFN LNGS)

Direct DM searches experimental techniques



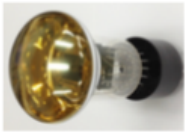
G.Dho

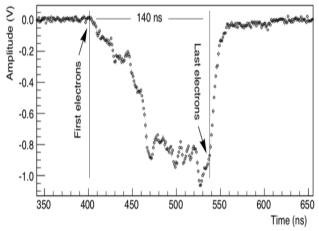
CYGNO/INITIUM



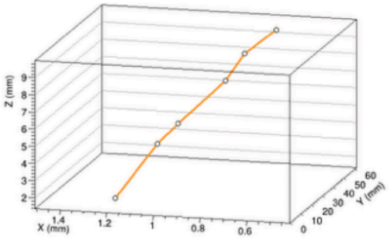
Gaseous Time Projection Chamber

Ionisation signal amplification & readout

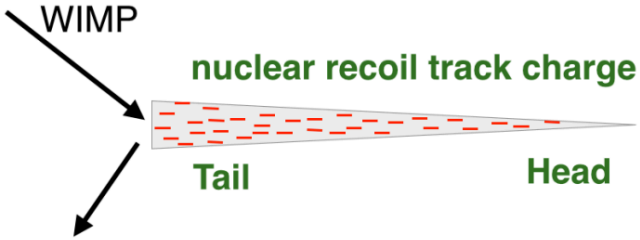




3D track with sensitivity to direction



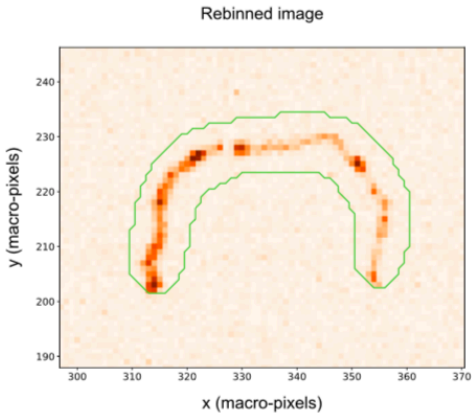
+ SF_6 for negative ion drift

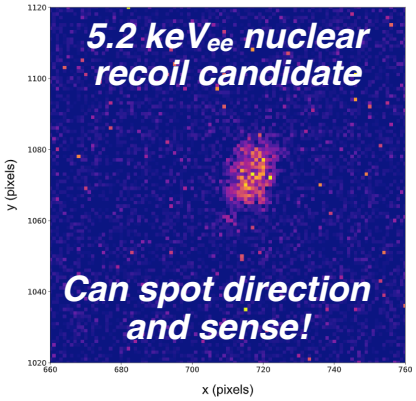


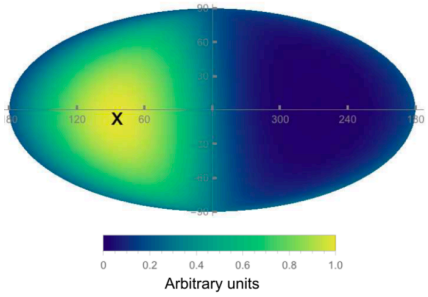
ER/NR discrimination via track topology + positive identification of DM signal via directional correlation

CHARGE

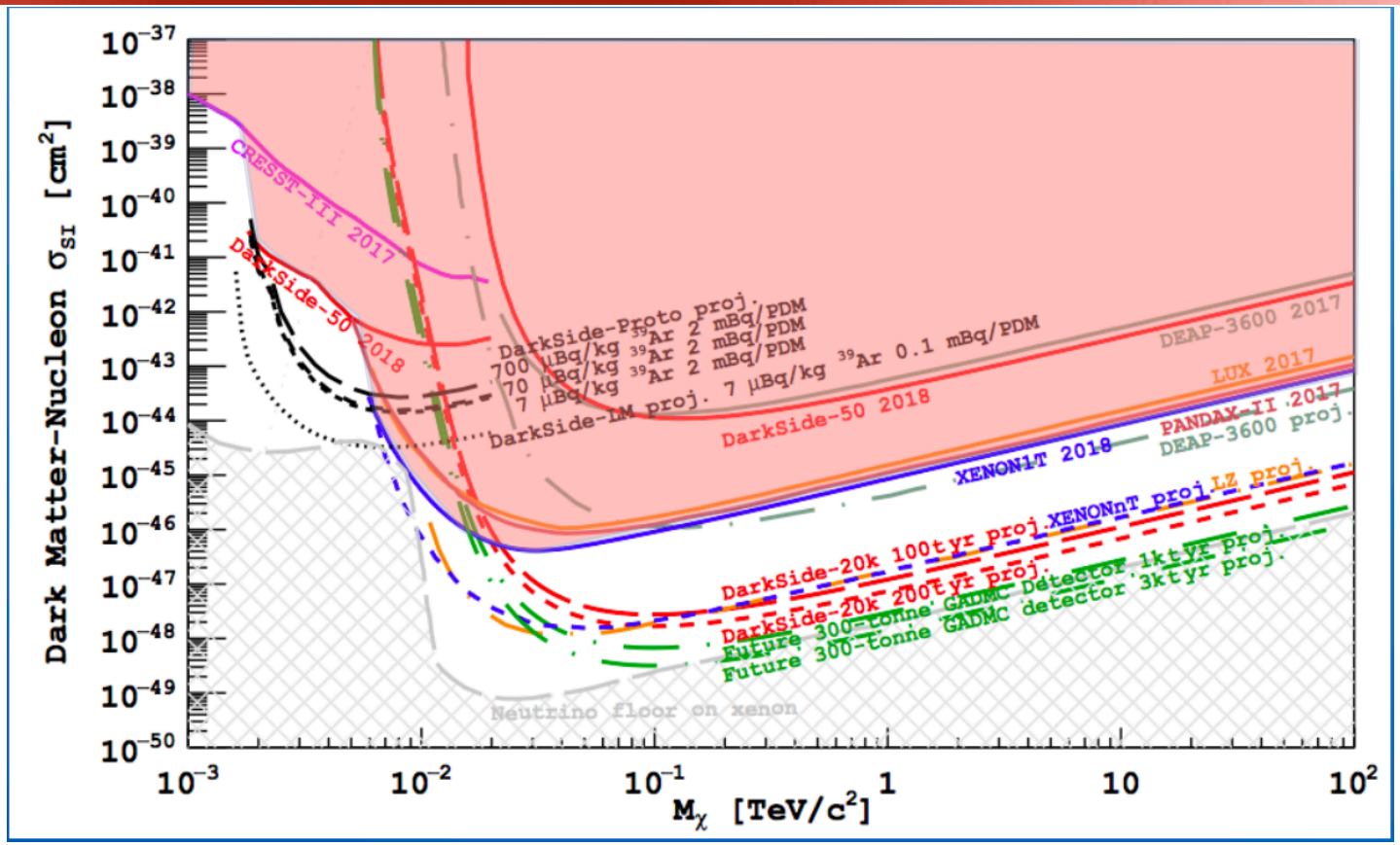
Directional detectors



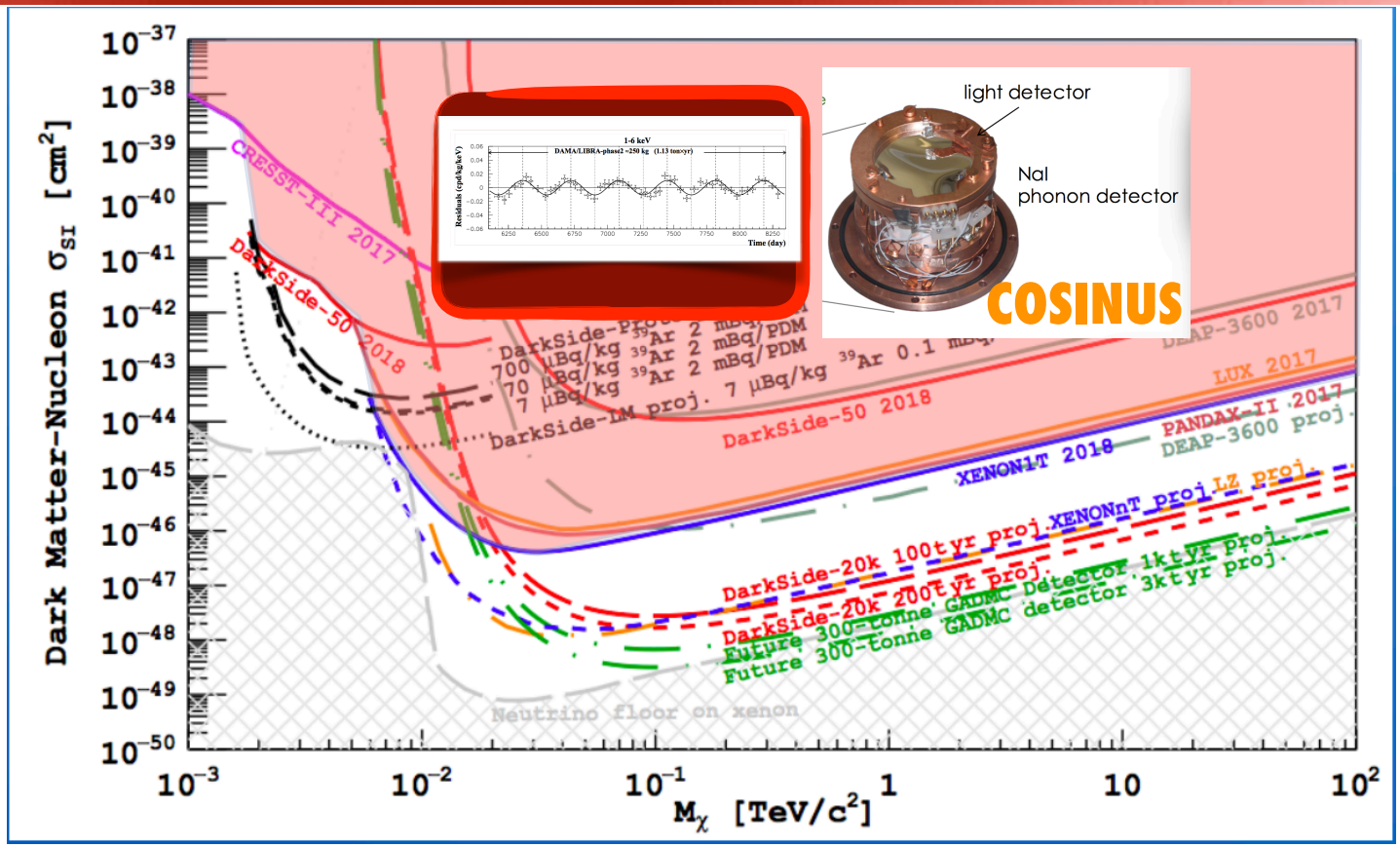




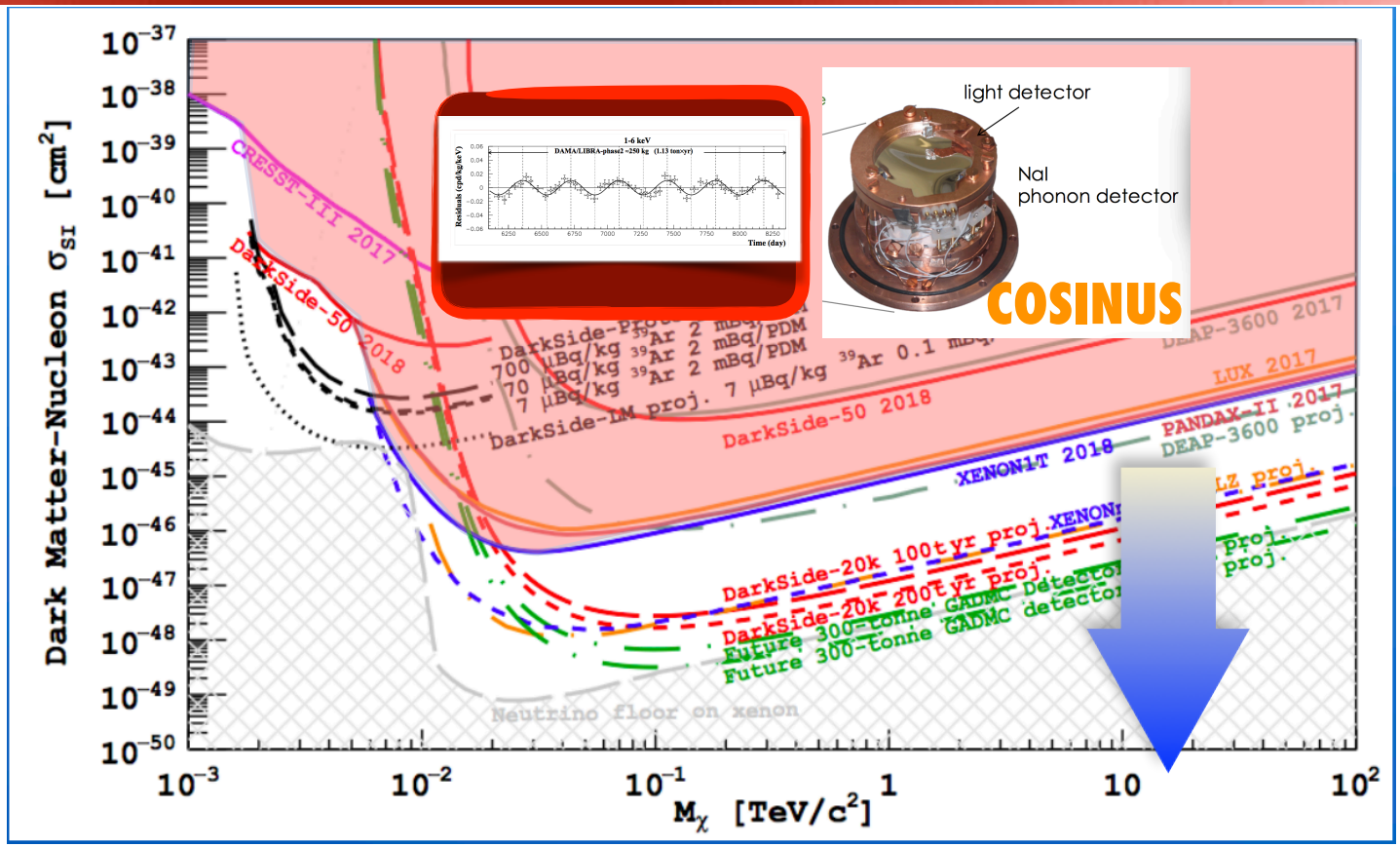
DM search panorama



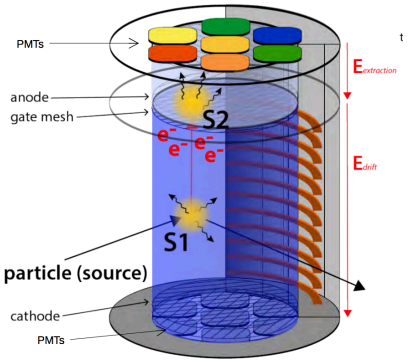
DM search panorama



DM search panorama

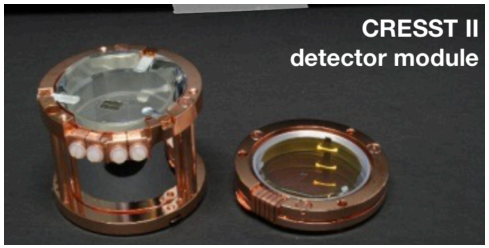


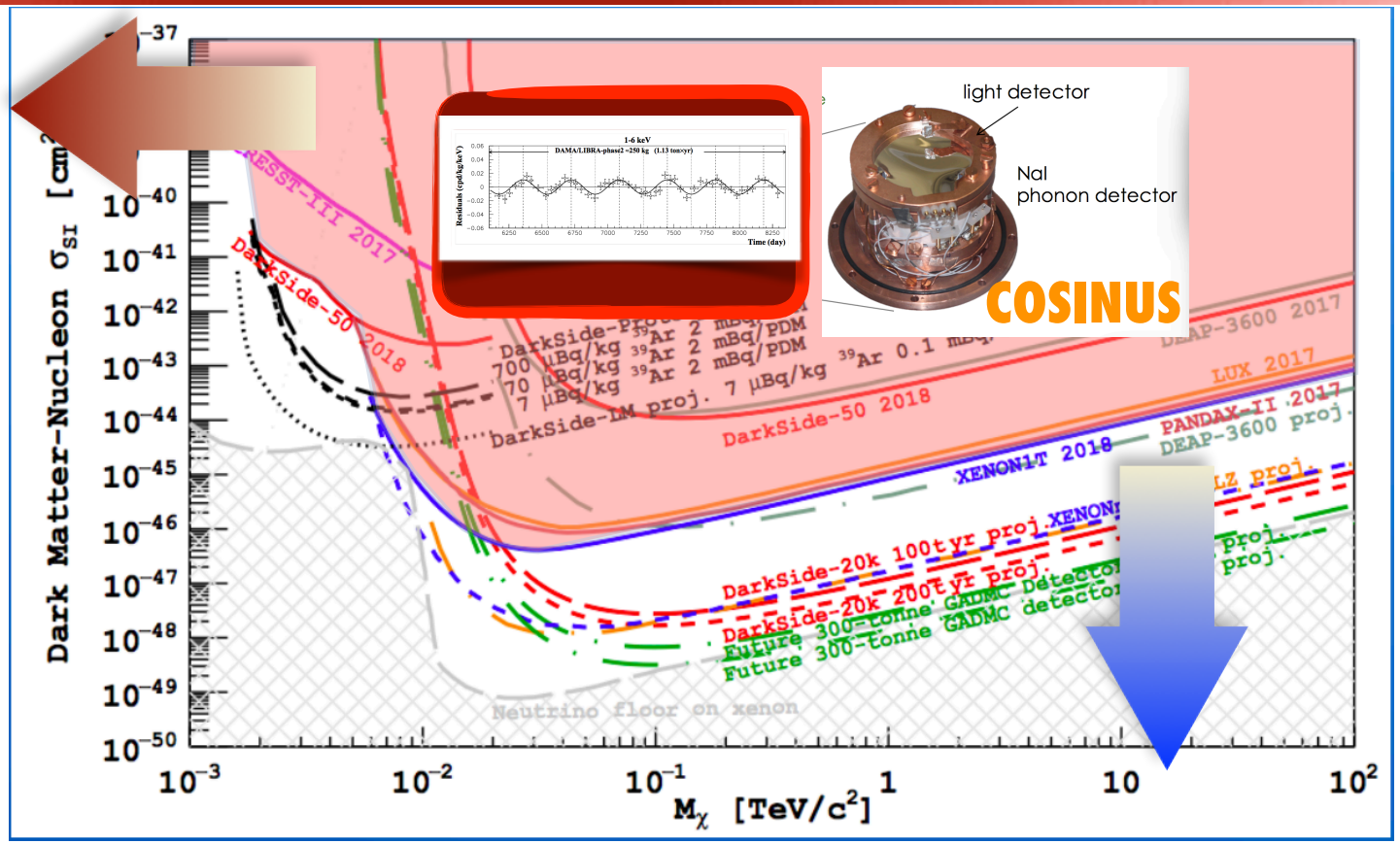
XenonNT & Darkside



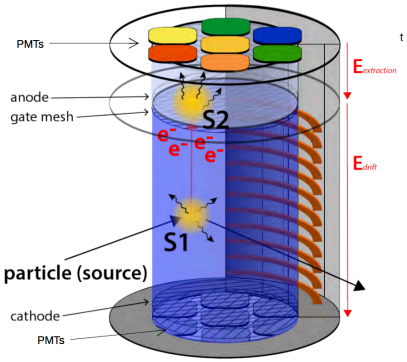
DM search panorama

CRESST



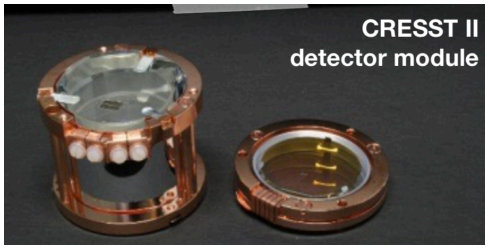


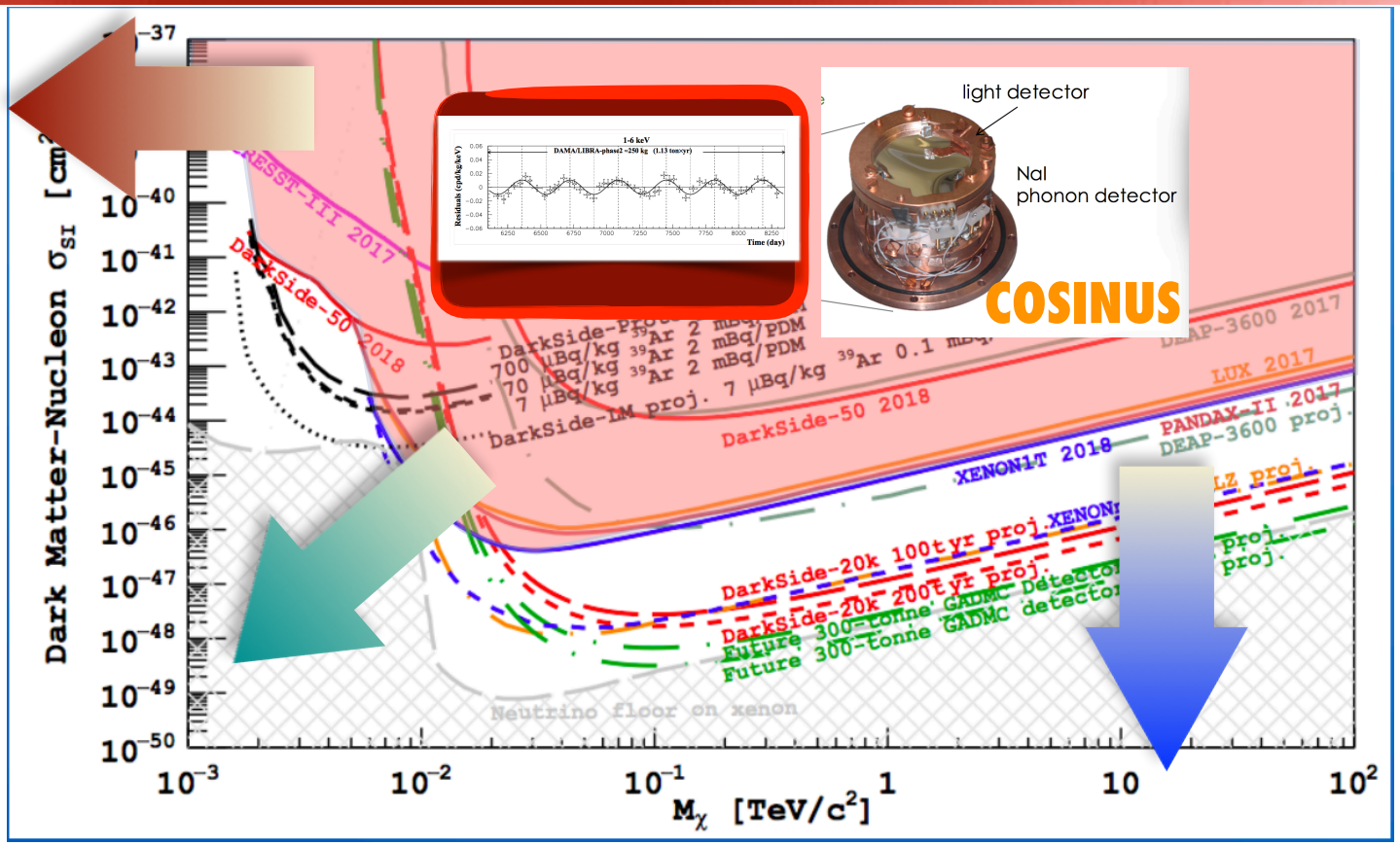
XenonNT & Darkside

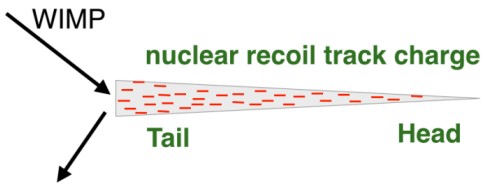


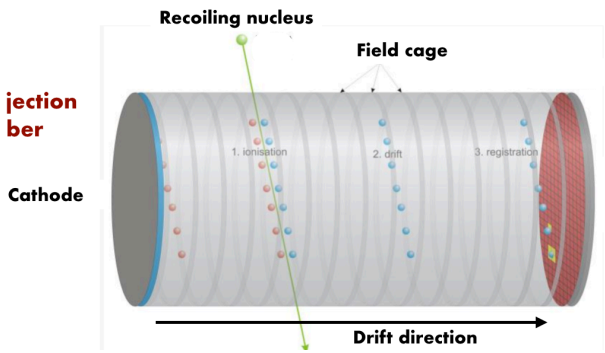
DM search panorama

CRESST





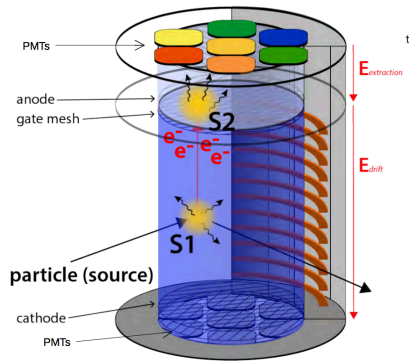




CYGNO/ INITIUM

Ionisation signal amplification & readout

XenonNT & Darkside

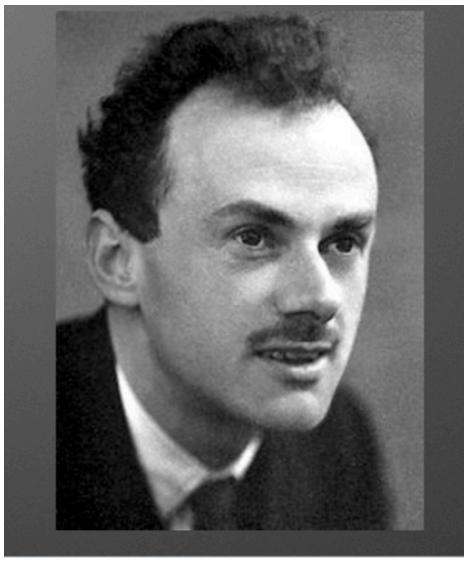


LE-TH1	E. LISI

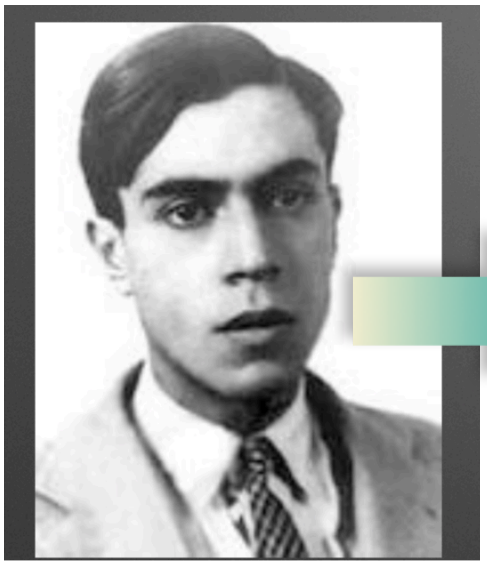
Neutrino Physics

LE-7: Neutrino oscillation experiments
Natalia Di Marco (GSSI and INFN)

The Neutrino nature



?

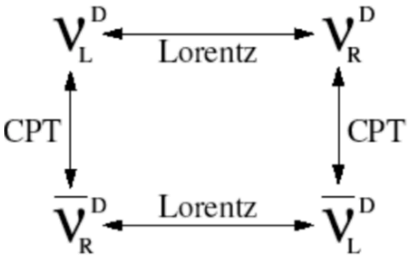


Neutrinoless double beta decay

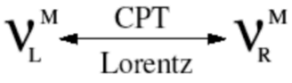
$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{|m_{\beta\beta}|^2}{m_e^2}$$

$$m_{\beta\beta} \equiv \left| \sum_{i=1,2,3} U_{ei}^2\, m_i \right|$$

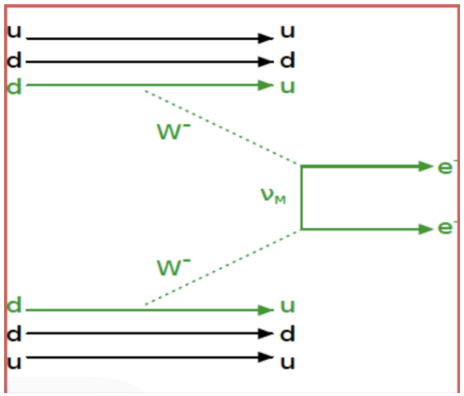
Measures effective electron neutrino mass

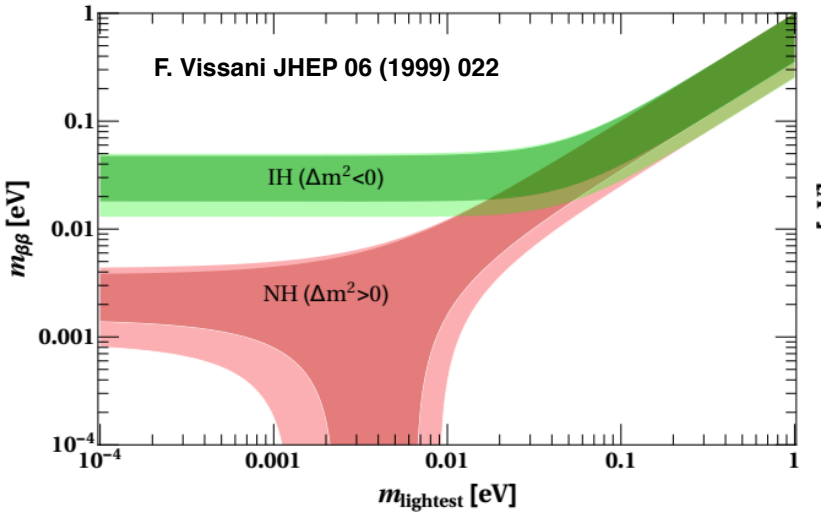


Dirac



Majorana





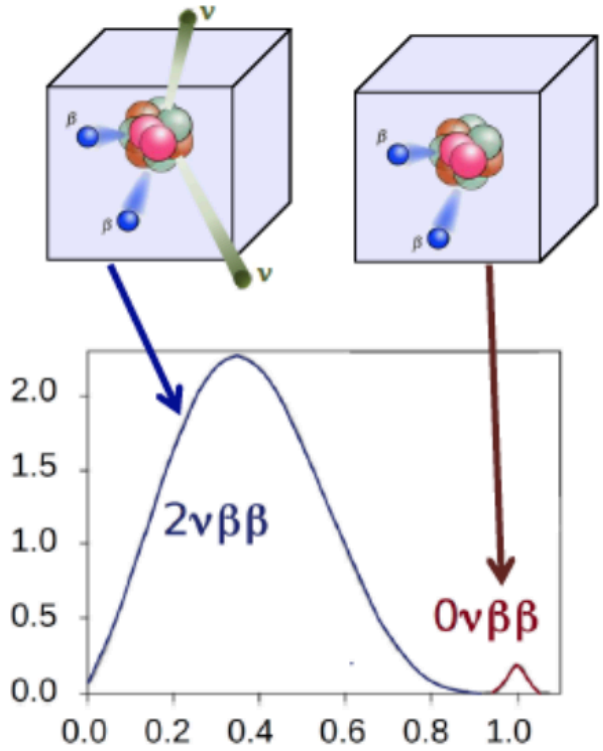
Test neutrino hierarchy

LE-EXP1	F. FERRONI

Neutrinoless double beta decay experiments @ LNGS

LE-EXP1	F. FERRONI

Approach:
SOURCE = DETECTOR



Main signature:
Peak at Q-value over 2νββ tail
enlarged only by detector resolution

$T_{1/2} > [10^{21}\text{-}10^{26}]$ years

$$N_{\beta\beta} = ln2 \times N \times t \times \varepsilon \frac{1}{T^{0\nu}_{1/2}}$$

$$\frac{1}{\sqrt{T^{0\nu}_{1/2}}} \propto \langle m_{ve} \rangle$$

$$S^{0\nu} \propto \epsilon\, i.a. \sqrt{\frac{MT}{b\Delta E}} \qquad b \neq 0$$

$$S^{0\nu} \propto \epsilon\, i.a.\, MT \qquad b = 0$$

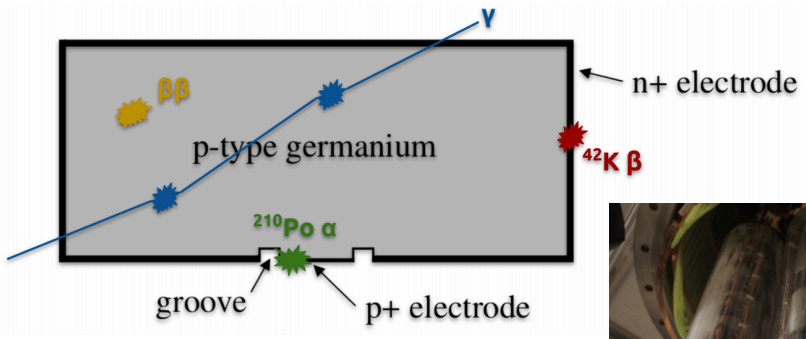
- M: Total active mass in kg
- ϵ: Detector efficiency
- $i.a.$: Isotopic abundance
- b: Background in c/keV/kg/y
- ΔE: Detector resolution @ ROI in keV
- T: Exposure time in y

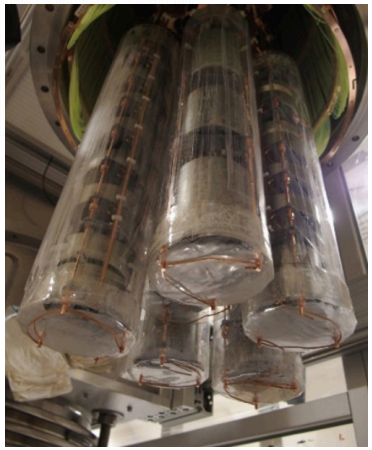
- Excellent energy resolution
- Low background
- Large masses of isotopes

N. Di Marco, M. Morella D. Helis

GERDA/LEGEND & CUORE/CUPID

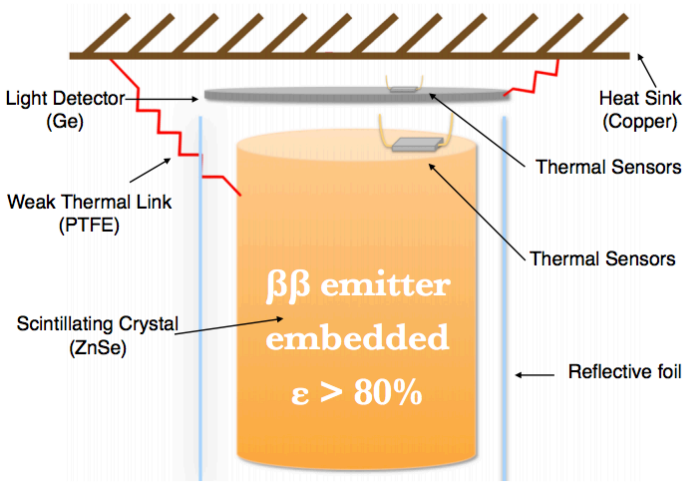
HPGe ionisation detectors

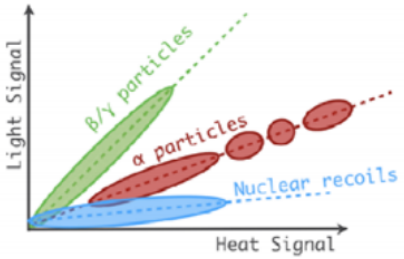




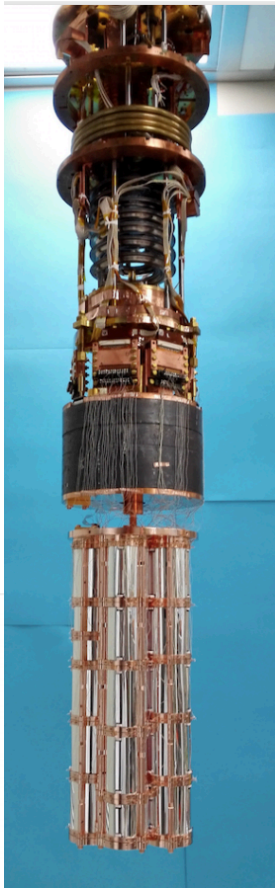
- PSD: Reject multi-site and surface events based on detector signal shape

(Scintillating) cryogenic calorimeters





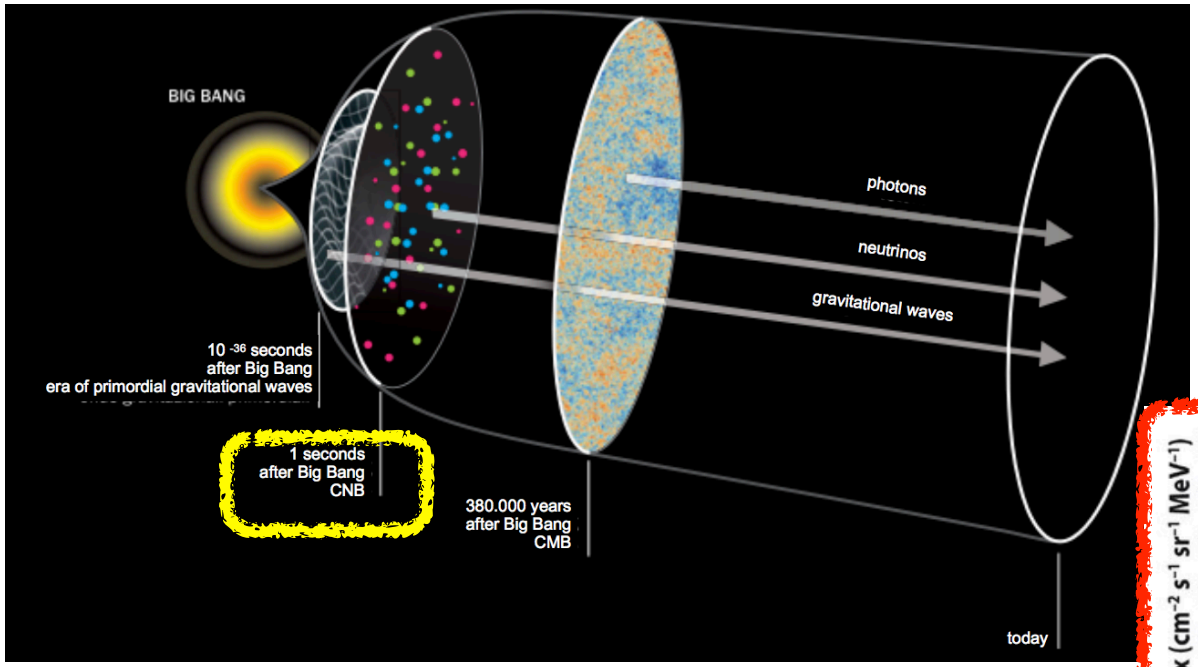
The simultaneous read-out of **HEAT** and **LIGHT** allows particle identification



GERDA/LEGEND **CUORE/CUPID**

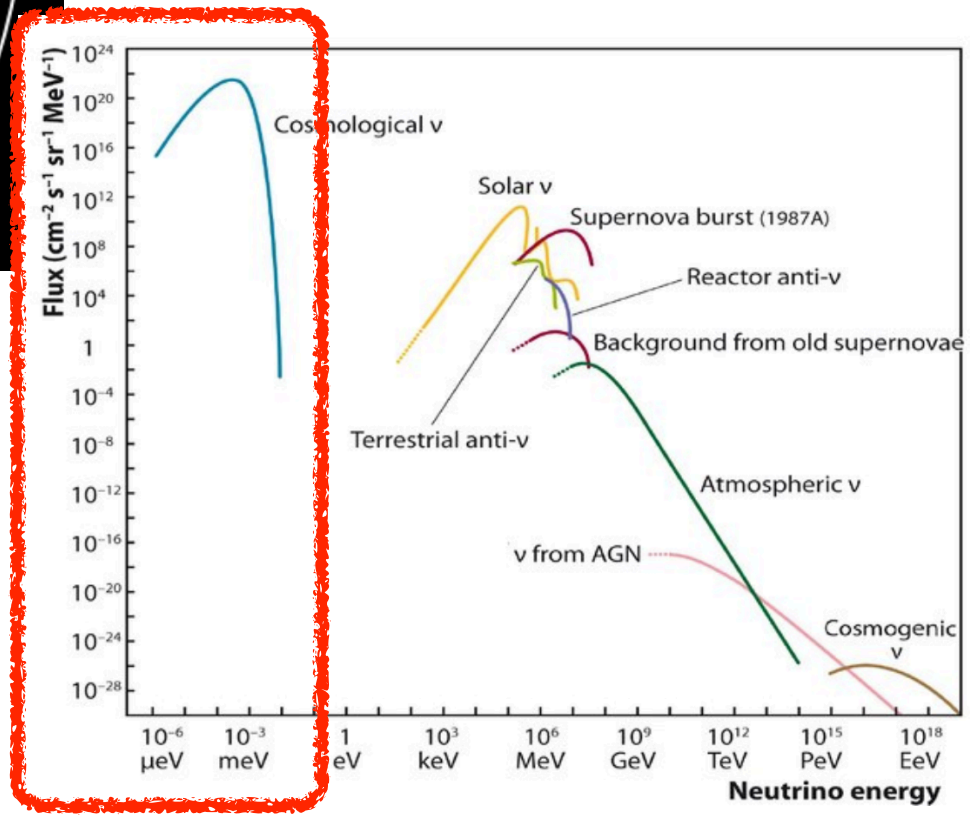
LE-8: Cryogenics sensors and related electronics
Andrei Puiu (GSSI and INFN), Marcello Messina (INFN LNGS)

Relic Neutrinos



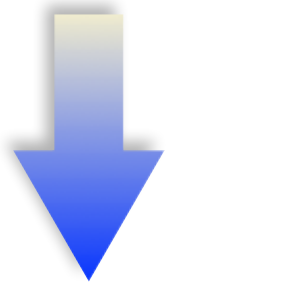
$$n \approx 56\ cm^{-3} \times 6$$

$$T \approx 1.9\ K \Rightarrow p_\nu \approx 0.001\ eV$$

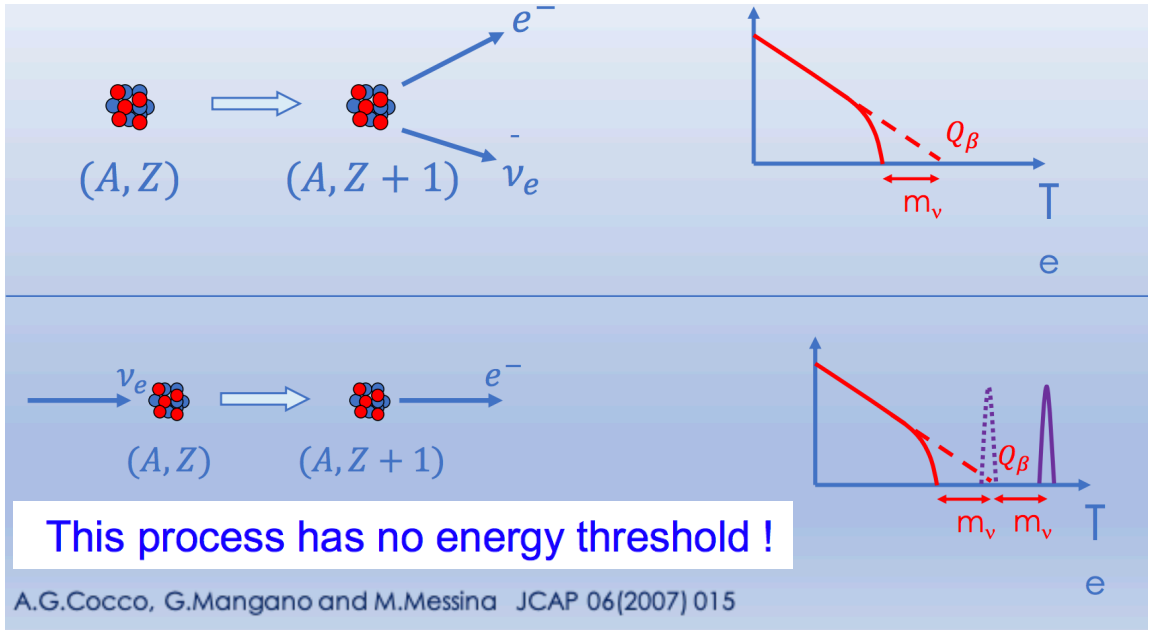


Relic neutrino detection principle

β decay



Neutrino Capture on a Beta decaying nucleus (NCB)

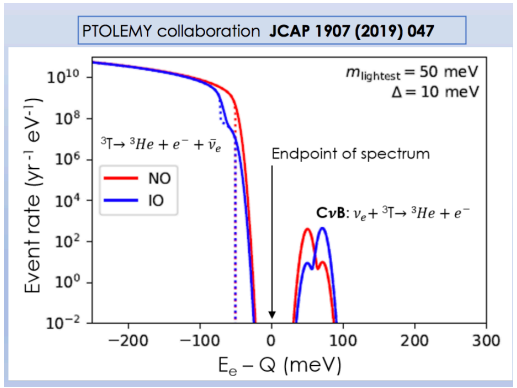


This process has no energy threshold !

A.G.Cocco, G.Mangano and M.Messina JCAP 06(2007) 015

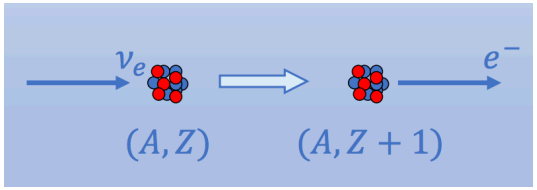
In Tritium:

- High cross-section for neutrino capture
- Sizeable lifetime
- Low Q-value
- **Tritium beta decay ~10^{15} Bq/gram**



M. Messina

Ptolemy experiment concept



Tritium Storage Cell
(Surface Deposition)

High Field Solenoid

Low Field
Region

~50-150eV
below
Endpoint

E_0-18.4keV

Filter removes
most low
energy e-

Long High Uniformity
Solenoid (~2T)

E_0+30kV

Cryogenic
Calorimeter
(σ~0.15eV)

0-1keV
(~150eV)

E_0

e-

e- from Tritium
start here

RF Tracking
(38-46 GHz)

Tracker
identifies e-

Calorimeter
measures e-

Accelerating
Potential

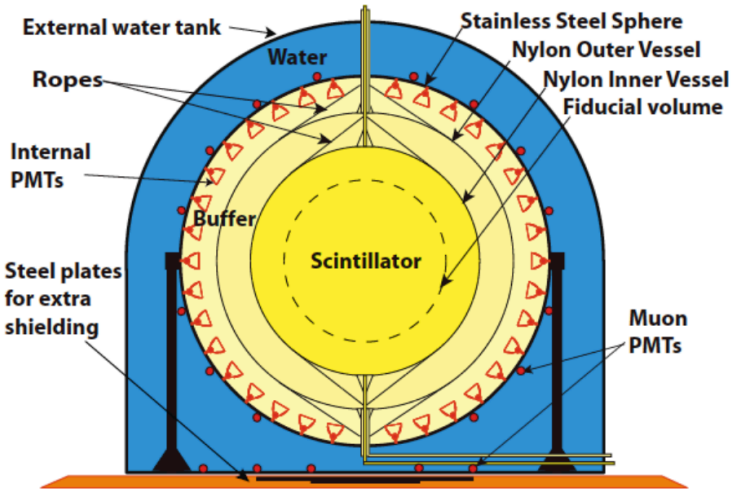
MAC-E filter
(De-accelerating
Potential)

Accelerating
Potential

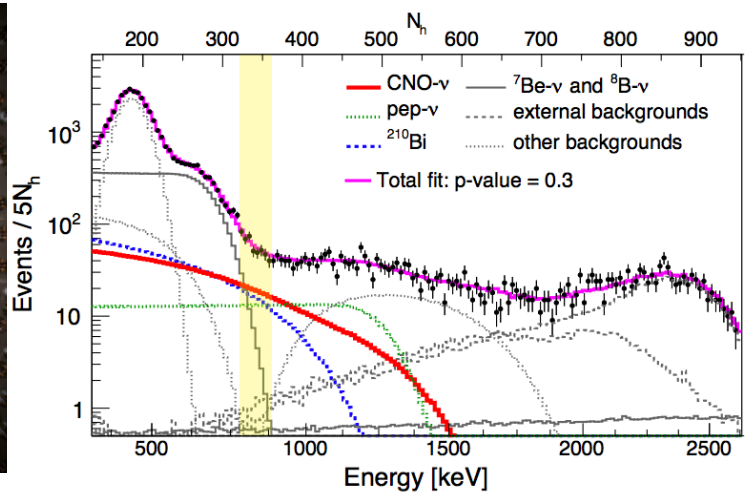
Time-of-Flight
(De-accelerating
Potential)

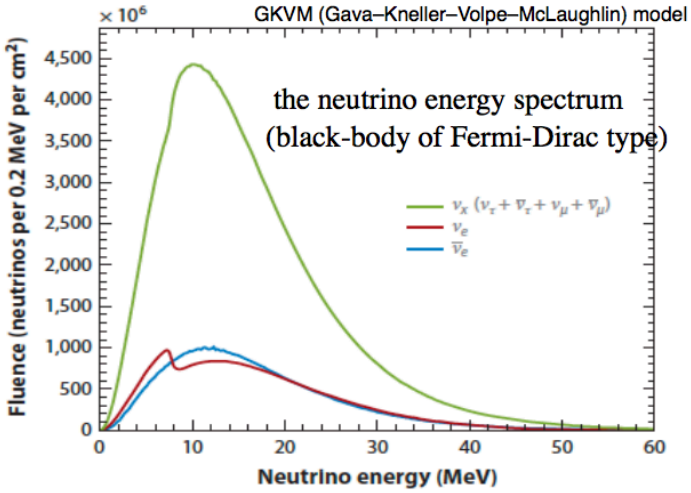
Solar & Supernovae neutrinos

Borexino



LVD



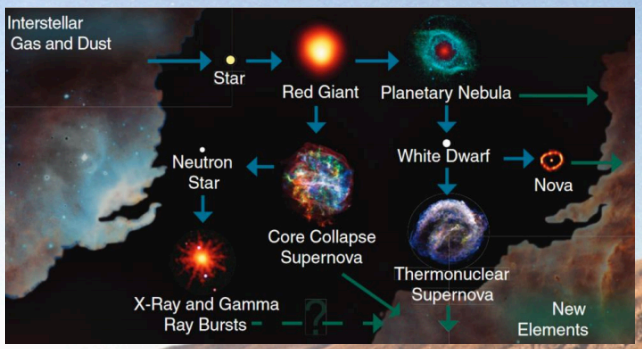


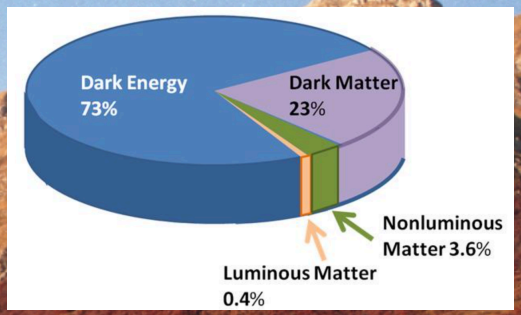
pp and CNO solar neutrinos measurements on Nature

Exploring the Universe from beneath the mountains

LE-4: Satistics tools for Astroparticle Physics
N. Di Marco (GSSI and INFN), S. Petrera (GSSI and INFN), F. Salamida (University of L'Aquila and INFN)

LE-6: Monte Carlo techniques
Luciano Pandola (INFN LNS)

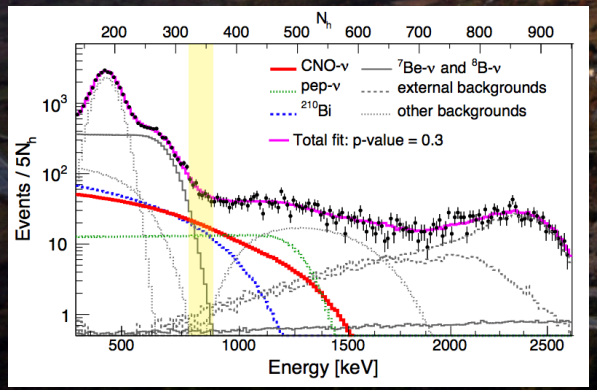


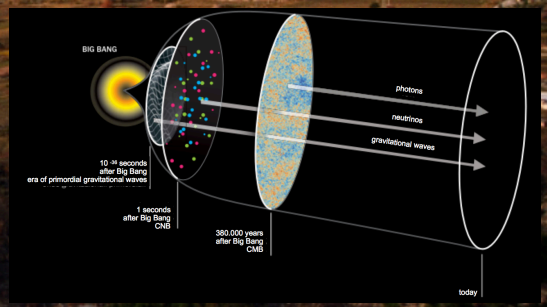


How the Universe was born and how it evolves

The solution to neutrino mystery

What the Universe is made of





A picture of the 1st second of the Universe