Dark Matter — Theory

Why do we need Dark Matter ?

- Rotation curves of galaxies
  - can be explained by Modified Newtonian Dynamics (MoND)
  - the gravitational dark matter could be macroscopic:
    - brown stars, planets, compact dust, . . .
    - Massive Compact Halo Objects (MaCHOs)

- Gravitational lensing
  - only needs the gravitational potential, not particles

- Mass balance in the expansion
  - todays measured value of the matter density id $\Omega_m \sim 0.27$
  - the visible mass (luminous and gas) has only $\Omega_{\text{lum}} \sim 0.04$

$\Rightarrow$ Structure formation and Baryon Acoustic Oscillations (BAO)

Structure formation

- density fluctuations grow through gravitational interaction:
  - overdense regions contract
    $\Rightarrow$ they become hot
  - underdense regions expand
    $\Rightarrow$ they cool down

- ”gas pressure” counteracts the contraction of dense regions
  - the density contrast δ follows the equation

$$\ddot{\delta} + [\text{Pressure} - \text{Gravity}]\,\delta = 0 \tag{1}$$

  - if $\text{Pressure} < \text{Gravity} \quad \Rightarrow$ exponential collaps
    - star formation; time of the collaps comparable to the Hubble time: $\sim \frac{1}{100} t_H$
  - if $\text{Pressure} > \text{Gravity} \quad \Rightarrow$ oscillations
    $\Rightarrow$ Baryon acoustic oscillations (BAO)

Dark Matter — Theory

Structure formation

- in the radiation era
  - most components are in thermal equilibrium
  - temperature defines the thermal speed of particles
  - most particles move fast enough to be ''radiation''

  $\Rightarrow$ hence ''radiation era''

- overdensities are washed out through the free streaming of ''radiation''
- the universe as a whole expands and cools down
  - particle species drop out of thermal equilibrium
    - $*$ and usually decay, thereby reheating the rest
  - stable non-relativistic particles form the matter density Ω_m
    - $*$ they should have no pressure

  $\Rightarrow$ their interaction has to be small

Dark Matter — Theory

Structure formation — observation

- galaxies (nebulae) are formed before the individual stars
  - star formation happens in the overdense nebulae
    - by fluctuatiuons in the overdense region
- the later the formation starts, the smaller the objects

$\Rightarrow$ at the start of structure formation
  - the free streaming length should be smaller than a galaxy
    - otherwise structure formation would not start . . .

- the cross section σ determines the mean-free-path of a particle

  = the length between two scattering events of the particle
    - the cross section σ is a measure for the interaction strength
  - if $\sigma|\vec{v}| < H_{\text{local}}$ the mean-free-path grows bigger than ℓ_H

  $\Rightarrow$ the particles effectively do not interact $\Rightarrow$ no pressure

Dark Matter — Theory

Structure formation — Dark Matter properties

- only a component already present in the radiation era
  can trigger structure formation
  - $\Rightarrow$ it has to be described by the Einstein-Boltzmann equations
    - $\Rightarrow$ Dark Matter ... and not macroscopic objects

- Dark Matter has nearly no pressure
  - does not participate in gravitational oscillations
    - $*$ described by the density contrast equation $\ddot{\delta} + [\text{pressure} - \text{gravity}]\,\delta = 0$
  - influences the BAO by providing additional gravitational attraction
    - $*$ effect is seen in the CMB spectrum

$\Rightarrow$ Dark Matter should not actively distort the CMB spectrum
- $\Rightarrow$ Dark Matter has to be electrically neutral
  - $*$ and can only very weakly interact with the CMB photons

Dark Matter — Theory

Structure formation — Dark Matter properties

- Big Bang Nucleosynthesis (BBN) happens in the radiation era
  - is successfully described by the Einstein-Boltzmann equations
  - Dark Matter should not spoil this success

    $\Rightarrow$ Dark Matter cannot interact by the nuclear force

$\Rightarrow$ Dark Matter can at most interact with the weak interactions

  $\Rightarrow$ Weakly Interacting Massive Particles (WIMPs)

  - WIMPs cannot decay quickly into Standard Model particles
    * otherwise the decay products would be energetic again
    * and disturb BAO and BBN
  - WIMPs are stable ... and form todays Dark Matter density

or

  - WIMPs decay into a hidden sector ...
    * which forms todays Dark Matter density

Dark Matter — Theory

Properties of the Dark Matter density

- can be several components, but should sum up to $\Omega_{\text{DM}} \sim 0.24$
- Baryonic Dark Matter
  - brown stars, planets, compact dust, ... MaCHOs
  - macroscopic objects $\Rightarrow$ non-relativistic
  - $\Rightarrow$ cannot contribute to structure formation
    - $\Rightarrow$ upper limit on contribution
- Non-Baryonic Dark Matter ... particles
  - Hot Dark Matter ... neutrinos or exotic very light particles (axions, axinos, ...)
    - ultra-relativistic still today: $v \sim c$ or $E_{\text{kin}} \gg m_0$
    - strongly influences structure formation: severe limit on contribution
  - Warm Dark Matter ... sterile neutrinos or gravitinos
    - relativistic still today: $E_{\text{kin}} \sim m_0$
    - also disfavoured by the current analysis
  - Cold Dark Matter (CDM) ... WIMPs
    - non-relativistic today: $E_{\text{kin}} \ll m_0$
    - the "standard" Dark Matter: weakly interacting and $m > 10$ GeV

Dark Matter — Theory

Particle Dark Matter

- Supersymmetric can provide all types

? How to get heavy particles stable ?

- the heavier a particle the quicker it decays:

muon	μ^-	0.105 GeV	$t_{1/2} = 2.2{\cdot}10^{-6}$ s
tau	τ^-	1.777 GeV	$t_{1/2} = 2.9{\cdot}10^{-13}$ s
top quark	t	172.2 GeV	$t_{1/2} = 5{\cdot}10^{-25}$ s

- a conservation law
  - for the Minimal Supersymmetric Standard Model (MSSM):
  - Matter parity $\mathcal{R}$
    * an assigned multiplicative quantum number
    * for each field f: $\mathcal{R}_f = (-1)^{3(B_f - L_f) + 2s_f}$

      with the baryon number B, the lepton number L and the spin s

$\Rightarrow$ the Lightest Supersymmetric Particle (LSP) is stable

Dark Matter — Theory

Supersymmetric Dark Matter

- the LSP has to be neutral under $U(1)_{\text{em}}$ and $SU(3)_{\text{color}}$
  - a partner of the neutral gauge bosons γ or Z
  - a partner of the neutral Higgses h^0 or H^0
    * or a mixture of these: a fermionic neutralino $\tilde{\chi}_k^0$
    * the standard choice
  - a partner of the neutral leptons, the neutrinos ν
    * or a mixture of these: a bosonic sneutrino $\tilde{\nu}_i$
    * disfavored by model building
- including gravity to SUSY gives Supergravity (SUGRA)
  - the partner of the graviton can be the LSP, too: the gravitino $\widetilde{G}$
    * even does not couple with the weak interaction
  - couples only gravitationally $\Rightarrow$ extremely weak: coupling $\sim \frac{E^2}{M_P^2} \sim 10^{-32}$
  - coupling not small in the GUT era with $kT \sim 10^{16}$ GeV

  $\Rightarrow$ thermal equilibrium at 10^{16} GeV and freeze-out during inflation ?

Dark Matter — Theory & Experiment

Supersymmetric Dark Matter

- the LSP could be the axino
  - the partner of the neutral axion
    - the Goldstone boson of the spontaneous broken symmetry of QCD vacua
  - the axion could couple to photons $\Rightarrow$ unstable

neutralino and sneutrino are weakly interacting — like the neutrino

- searching for Dark Matter particles
  - in Neutrino Telescopes or specialized experiments
  - signals reported from DAMA, CDMS, and CRESST
    - but the determination of the Dark Matter parameters is still incompatible
- producing Dark Matter particles at the LHC
  - detecting them in cascade decays
  - since they do not interact with the nuclear interaction
    - they are not directly produced

Dark Matter Detection — Basics

How do we "see" ?

- All macroscopic interactions are electromagnetic
  - chemical bonds making molecules
- Effects of the chemical bonds describe the macroscopic physics
  - crystal made by lattices of ions, held together by
    - different polarity of the ions: ionic crystals
    - or by the electron gas: metals
  - liquids are bound by the Van der Waals forces
  - gases are defined by the repulsion of the electron shells
- friction is just the stretching or ripping of these chemical bonds
- Gravity only matters at the cosmic scale
  - Planetary orbits, stellar orbits, galaxies, etc. ...
  - Earths gravity gives "only" a background for particle physics

How do we "see" subatomic particles ?

- Since all macroscopic interactions are electromagnetic
  - $\Rightarrow$ we have to see them with their electromagnetic interactions !

$\Rightarrow$ We only see charged particles directly !

  - – neutral particles have to interact somehow else, that we can see their charged reaction products

- Subatomic particles follow Quantum Mechanics
- Detectors are macroscopic devices
  - $\Rightarrow$ Subatomic particles interact with the detector "classically"
    - $*$ they behave like a small charged ball
  - – they loose energy and momentum in passing through material
    - $*$ this is how we can detect them

Dark Matter Detection — Basics

How do we ”see” subatomic particles ?

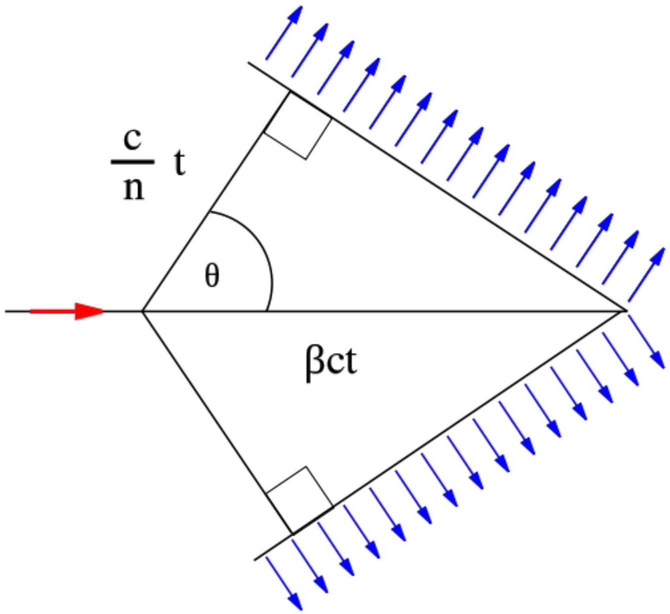
- charged particles are ”ionizing”
  - when a charged particle passes through a material, it can strip off electrons from the atoms
    - ∗ they are part of the ionizing radiation

  ⇒ Geiger counters
  - development of Geiger counters gives
    - ∗ Wire chambers
    - ∗ Spark chambers
    - ∗ modern semiconductor detectors
  - other uses of the ionizing nature of charged particles
    - ∗ Cloud chamber
    - ∗ Bubble chamber
- if a charged particles moves faster than c_{material}:

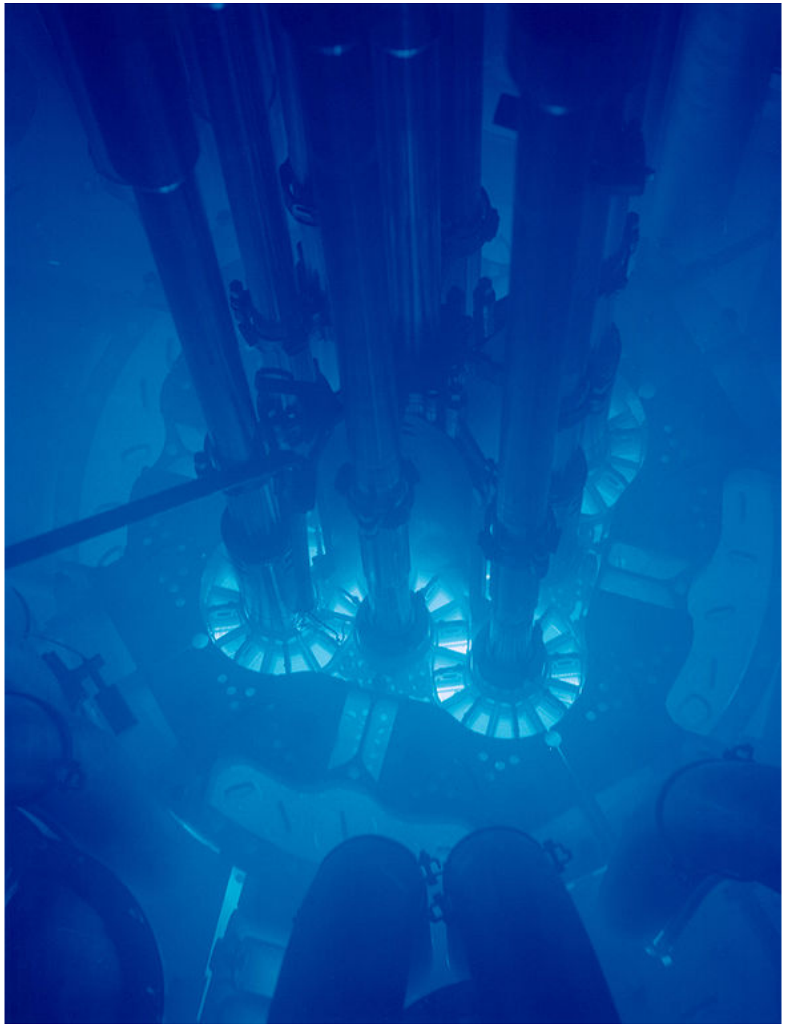
  ⇒ Cherenkov radiation ⇒ Cherenkov counters

Schematic and picture of Cherenkov radiation

- used in detectors
  - Neutrino detectors
  - Cosmic Ray detectors
  - Particle detectors

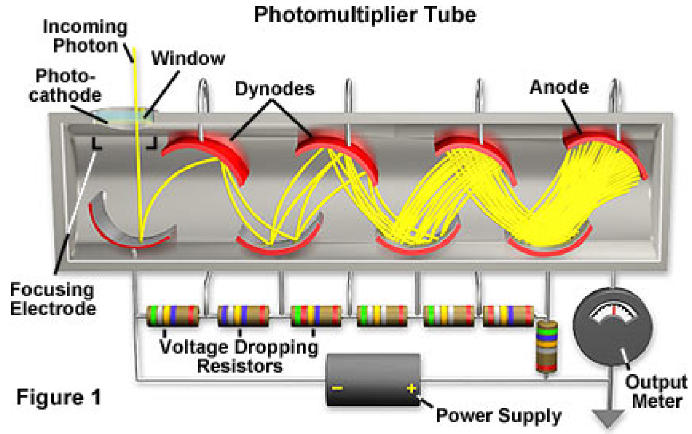


The geometry of the Cherenkov radiation
(shown for the ideal case of no dispersion)



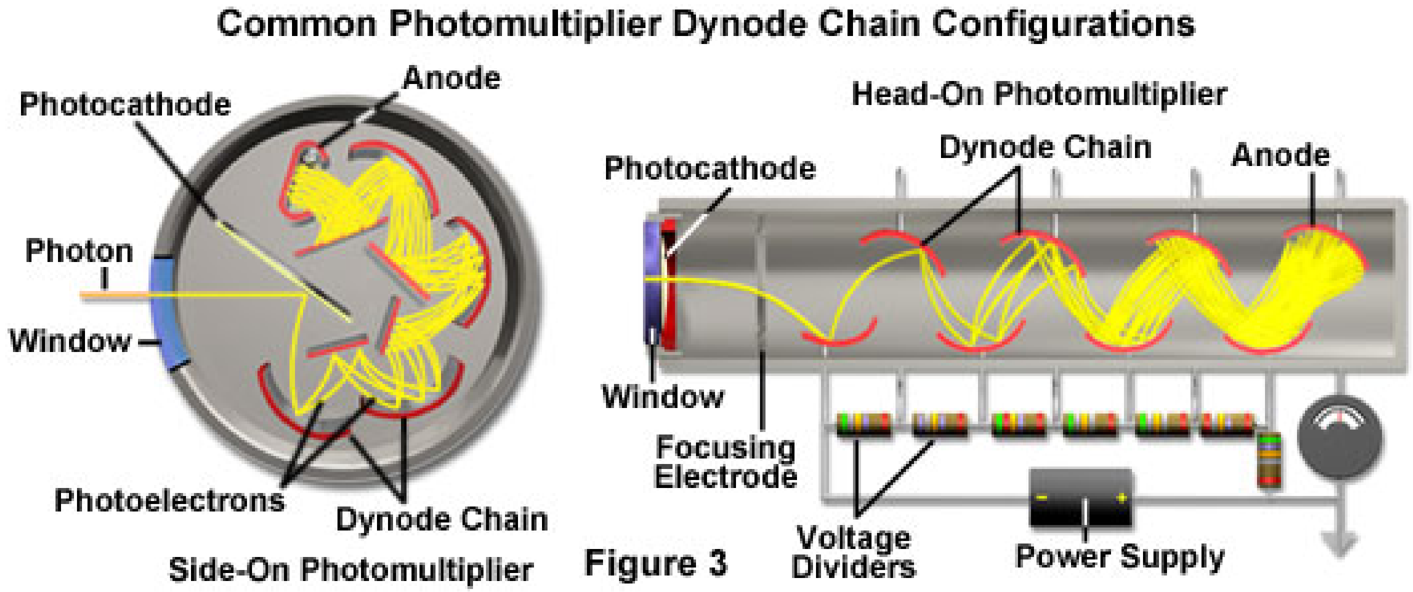
Cherenkov radiation glowing in the core of the Advanced Test Reactor (ATR) at the Idaho National Laboratory, USA

Dark Matter Detection — Photon



"Seeing" neutral particles: the photon

- We see the photons with our eyes . . .
  - but not single photons
  - and not photons of every energy
- single photons can be seen by photomultipliers
  - using the photoeffect to produce electrons, that are then amplified through a cascade
  - not usable for the highest energy photons

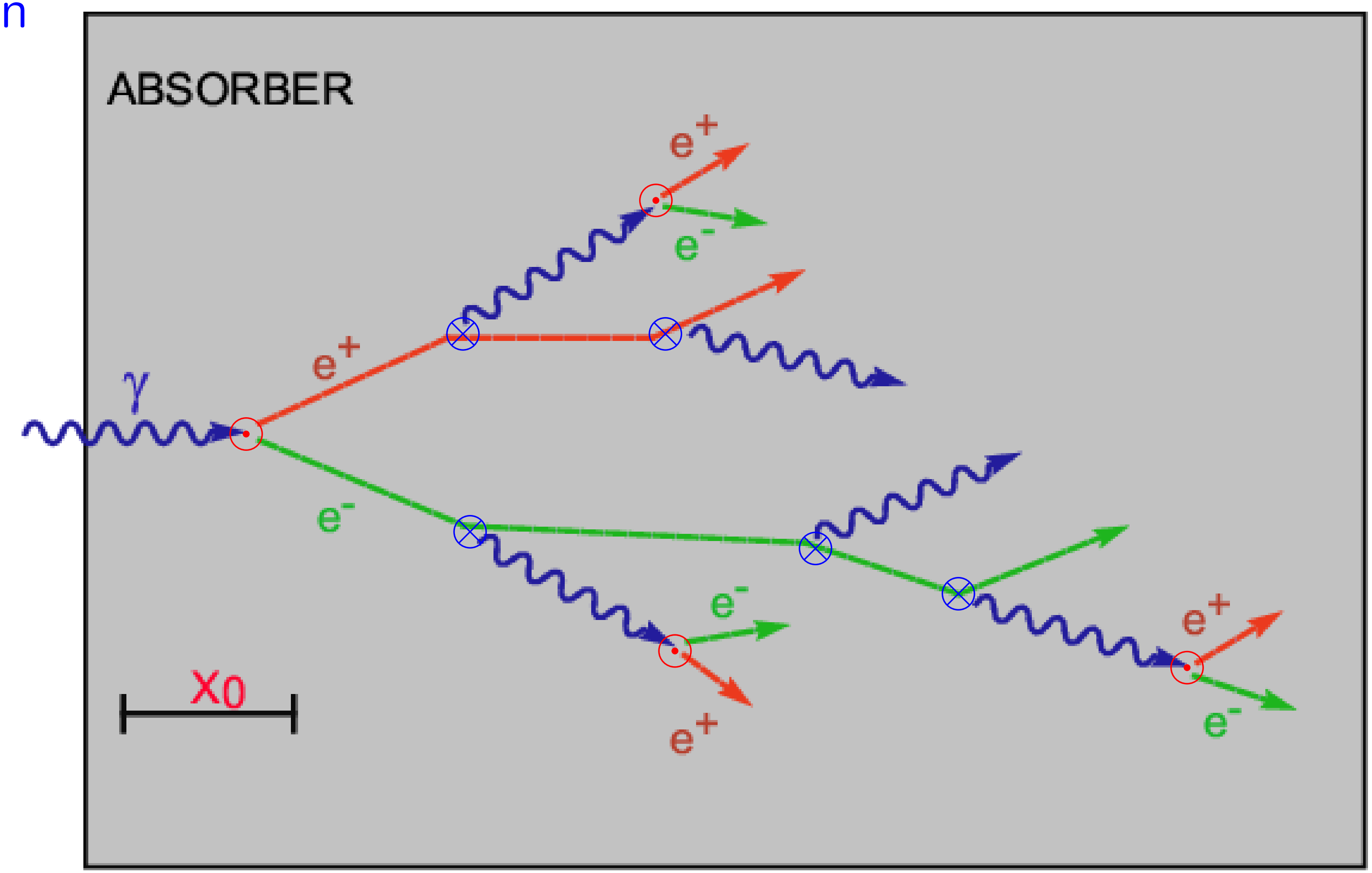


Dark Matter Detection — Photon

"Seeing" neutral particles: the photon

- in matter photons can convert into electron-positron pairs

  $\Rightarrow$ Pair conversion



- a heavy nucleus is necessary for momentum conservation
- a single photon in vacuum cannot decay

the mechanism of the cascade uses

- Bremsstrahlung $\otimes$
- Pair production $\odot$

Dark Matter Detection — Neutrino

"Seeing" neutral particles: the neutrino

- the neutrino has only weak interactions
  - every interaction has to be mediated by the $W^{\pm}$ or Z^0 boson

  $\Rightarrow$ strong suppression at less than exreme energies
    * extreme energies means: $$E_\nu > \frac{m_W^2}{m_{p\,(e)}} \tag{2}$$

  $\Rightarrow$ interaction with proton (neutron): $E_\nu >$ 6.4 TeV

  $\Rightarrow$ interaction with electron: $E_\nu >$ 13 PeV $(= 13 \cdot 10^6$ GeV)

- $W^{\pm}$ mediated interaction: charged current
$$\nu_\ell + X \to \ell + Y \quad \text{with} \quad \ell = e, \mu, \tau \tag{3}$$
  - X and Y are often nuclei and have the same mass

  $\Rightarrow$ neutrino energy has to be bigger than m_ℓ $\Rightarrow$ threshold

- Z^0 mediated interaction: neutral current
$$\nu_\ell + X \to \nu_\ell + X \qquad \Rightarrow \quad \text{no threshold} \tag{4}$$

Dark Matter Detection — Neutrino

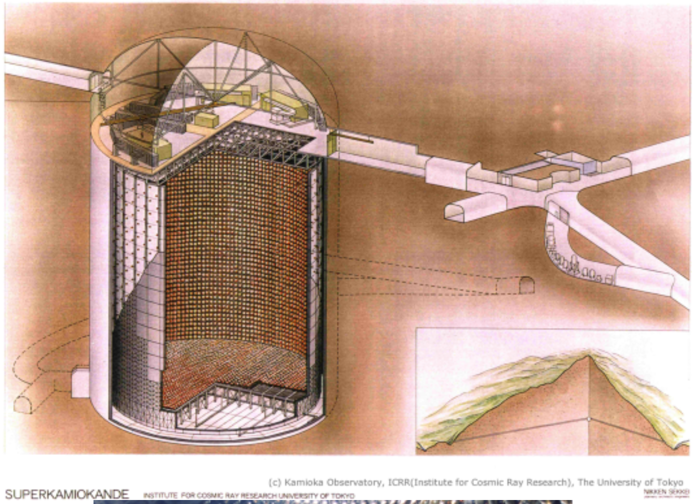
detecting the neutrino through

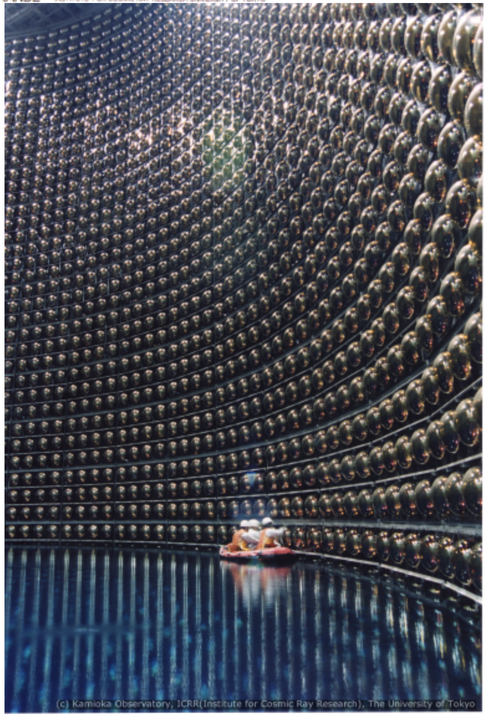
- radio chemical methods (inverse beta decay): charged current
  - $$\nu_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^- \qquad (5)$$
    * first solar neutrino measurement in the Homestake Experiment (1970-1994)
  - $$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^- \qquad (6)$$
    * the followup experiments SAGE (1989-2010) and GALLEX (1991-1997)
- Cherenkov light from scattered electrons
  - charged and neutral current: $$\nu_e + e^- \to e^- + \nu_e \qquad (7)$$
  - threshold: the scattered e^- has to have $$v_e > c_{\mathrm{mat}} = \frac{c}{n} \qquad (8)$$

  $\Rightarrow$ $E_\nu >$ few MeV
    * Kamiokande, Super-K, SNO, MiniBooNE, NEMO, AMANDA, ...
- scintillator light from scattered electrons
  - similar to Cherenkov detector
  - but lower threshold: $E_\nu > 250$ keV
    * Borexino, Daya Bay, Double Chooz, Minos, ...

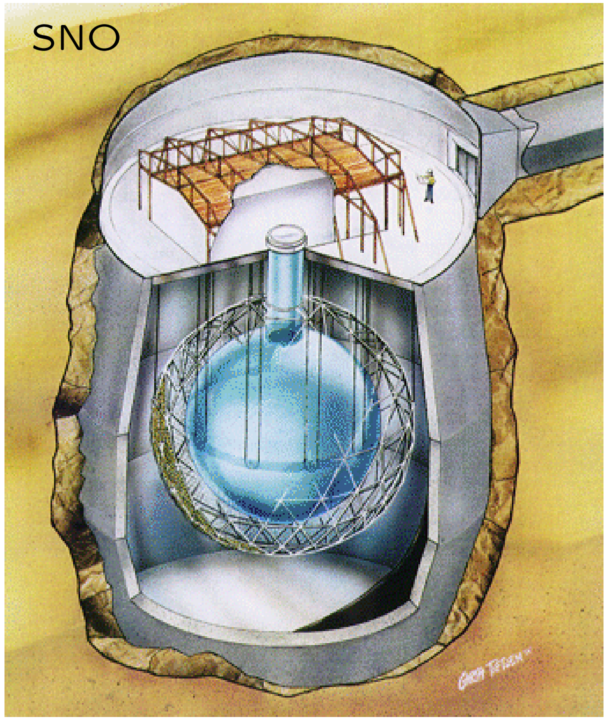
Dark Matter Detection — Neutrino

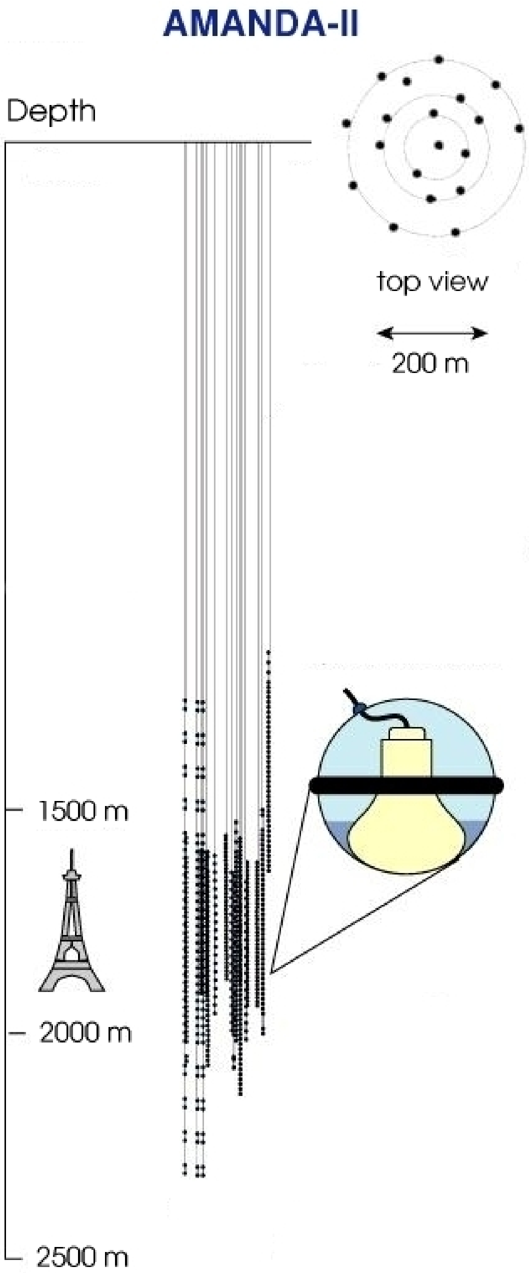
Super-K





Borexino





Dark Matter Detection — LSP

"Seeing" the supersymmetric neutralino / sneutrino (LSP)

- the LSP also has only weak interactions
  - interaction similar to the neutrino
  - difference to the neutrino: the LSP is much heavier $m_{\mathsf{LSP}} \gg m_\nu$

  $\Rightarrow$ bigger momentum transfer at lower energies

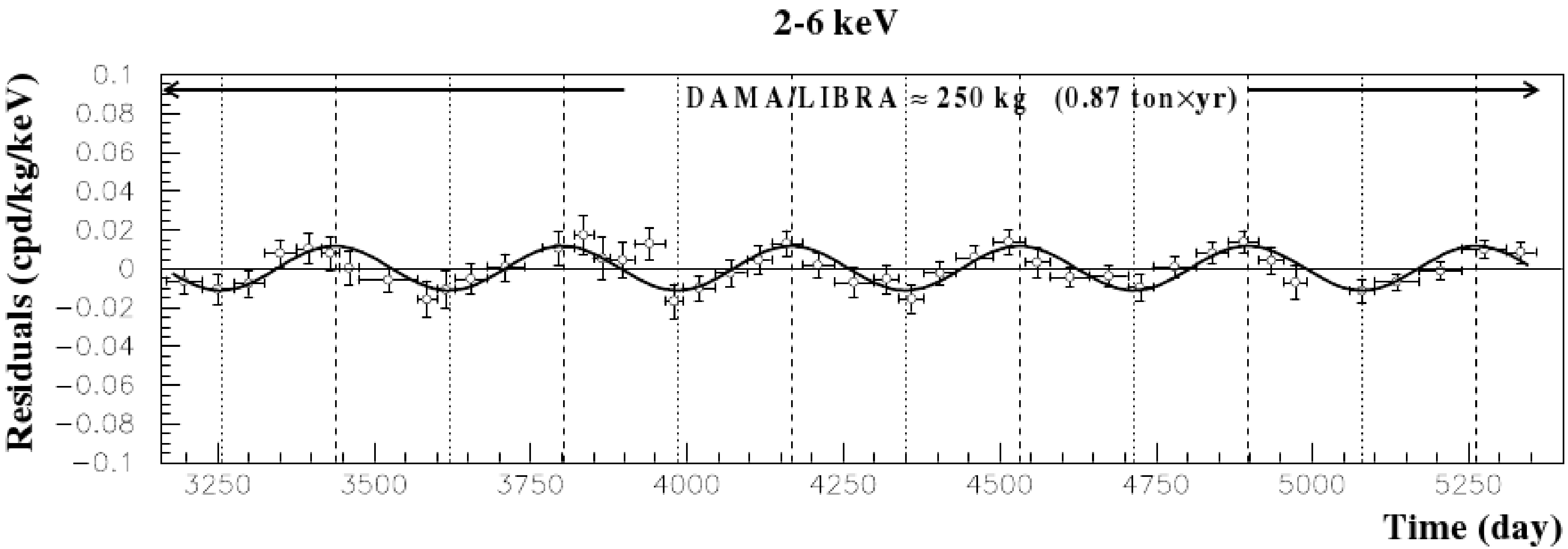
  $\Rightarrow$ additional detection possibilities

- cryogenic crystal absorbers
  - measuring ionization and phonons from the interaction
    - CDMS, CRESST, EDELWEISS, EURECA (under construction) ...
- noble gas liquid scintillator detectors
  - measuring scintillation and pulse shape from the interaction
    - DAMA, ZEPLIN, XENON, DEAP, ArDM, WARP (planned), LUX (planned) ...
- modified bubble detectors
  - measuring the phase transition of superheated droplets
    - SIMPLE and PICASSO

Dark Matter Detection — LSP

"Seeing" the supersymmetric neutralino / sneutrino (LSP)

- DAMA/NaI, DAMA/LIBRA sees an annual modulation of a signal
  - consistent with the expectation of a DM flux
  - the only "signal" is the modulation of the signal
  - but this modulation is a 8.9σ CL effect
    * DAMA/NaI, DAMA/LIBRA is the only NaI experiments

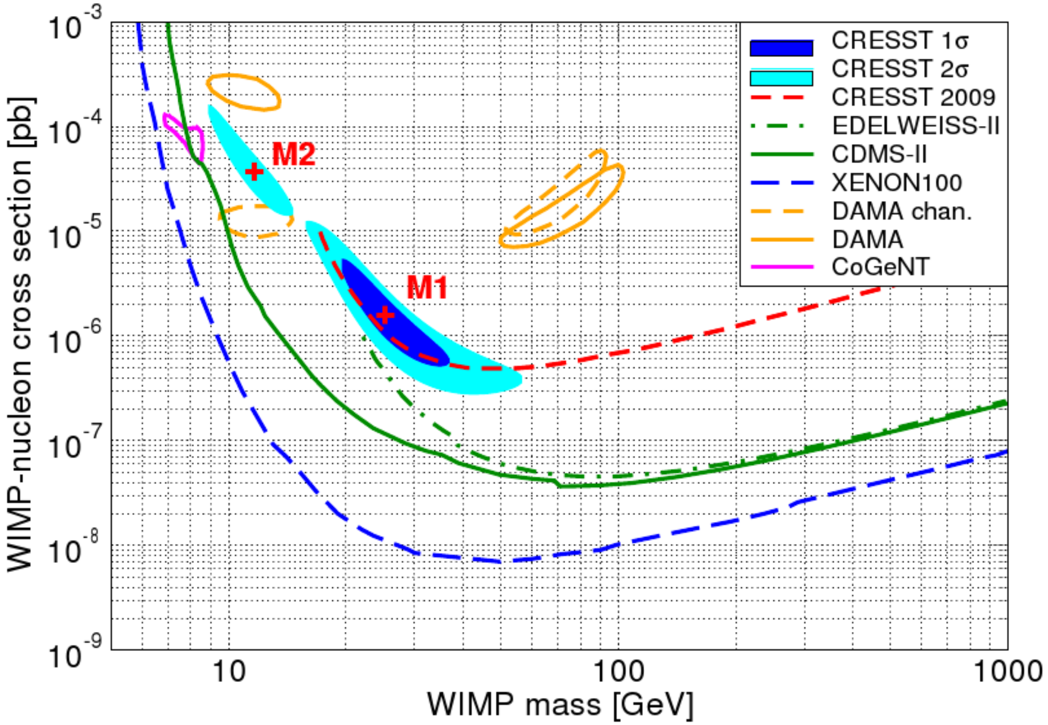


- no signal in the other noble gas liquid scintillator detectors

Dark Matter Detection — LSP

"Seeing" the supersymmetric neutralino / sneutrino (LSP)

- CRESST sees 67 events
  - with ~ 40 expected from background
  - $\Rightarrow$ exclusion of the background-only hypothesis with nearly 5σ
- EDELWEISS sees 5 events
  - with < 3 expected from background



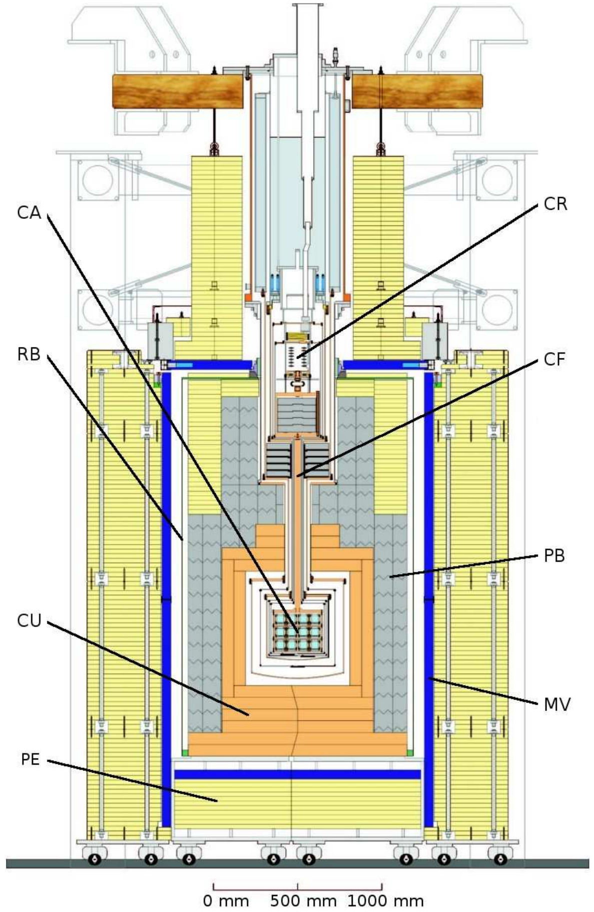
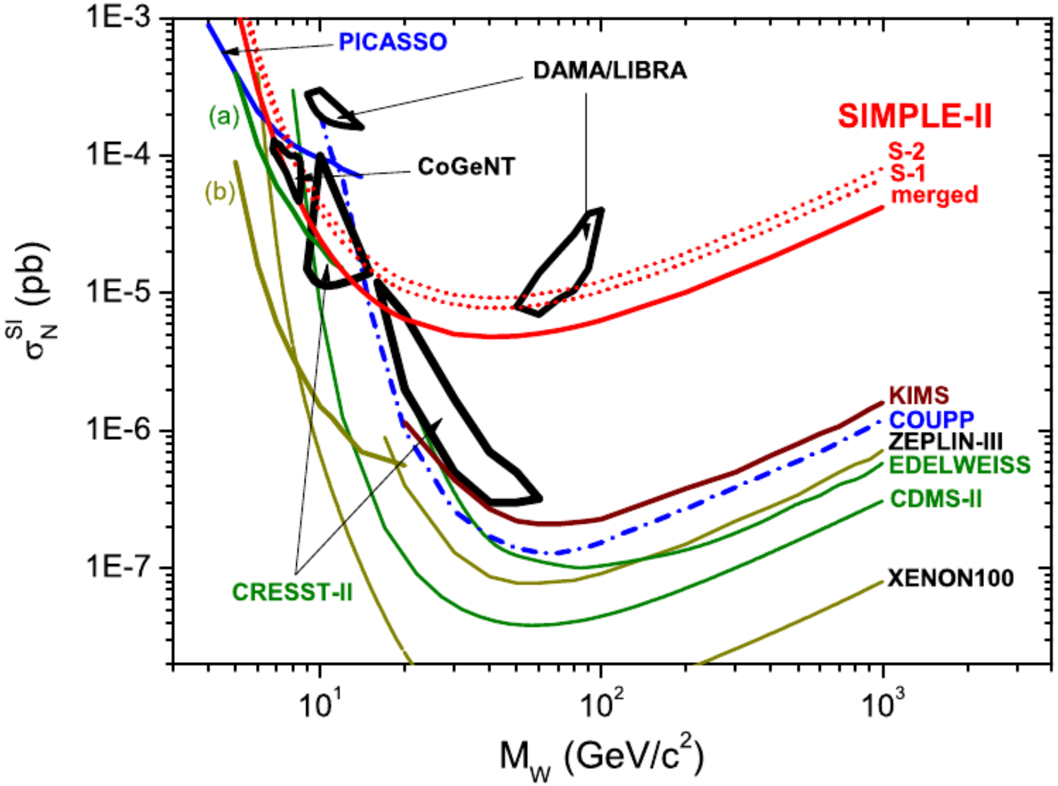


Fig. 4. Schematic drawing of the CRESST setup. A cold finger (CF) links the cryostat (CR) to the experimental volume, where the detectors are arranged in a common support structure, the so-called carousel (CA). This volume is surrounded by layers of shielding from copper (CU), lead (PB), and polyethylene (PE). The copper and lead shieldings are additionally enclosed in a radon box (RB). An active muon veto (MV) tags events which are induced by cosmic radiation.

Dark Matter Detection — LSP

"Seeing" the supersymmetric neutralino / sneutrino (LSP)

- SIMPLE and PICASSO see no signal
  - but supposedly cover the parameter region of DAMA and CRESST



SIMPLE: production of the superheated droplet detectors

Dark Matter Detection — LSP / gravitino

"Seeing" the supersymmetric neutralino / sneutrino (LSP)

- LHC sees no signal for SUSY (yet?)
  - but the LSP can only be produced through a decay chain
  - if the directly producable particles are too heavy

  $\Rightarrow$ no chance of seeing the LSP

"Seeing" the gravitino

- direct detection experiments have no chance
  - the cross section is much too small (by a factor of 10^{-20})
- if the LHC can produce SUSY particles
  - they will decay finally into the gravitino

  $\Rightarrow$ in that case the LHC has a chance to detect the gravitino