Dark Matter in the Universe

physics beyond the standard model

how to detect Dark Matter particles

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‘Standardmodel’ of Cosmology

<table>
<thead>
<tr>
<th>Component</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Energy</td>
<td>$\Omega_{\text{vac}} = 73%$</td>
</tr>
<tr>
<td>Dark Matter</td>
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</tr>
<tr>
<td>normal Matter</td>
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Standardmodel of Particle Physics

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<th>Possible explanations beyond the Standardmodel</th>
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⇒ Physics beyond the Standardmodel
⇒ at least one of the ‘standards’ has to be changed (most likely both)
⇒ (direct) Dark Matter search is testing both
⇒ exciting times
many astrophysical observations point to Dark Matter?

orbital motion around Galaxies
or motion of galaxies in galaxy clusters too fast

gravity potential and distribution of visible matter do not coincide

light deflection shows higher gravity potentials than expected from visible matter
Anisotropy of Cosmic Microwave Background

\[ p + e^- \rightarrow H + \gamma \]

Wilkinson Microwave Anisotropy Probe
Dark Matter Search

Universe not transparent

$p + e^-$

Universe transparent

CMB

Universe transparent
perfect black body  $T = 2.73K$

tiny anisotropy $\sim \delta T / T \sim 10^{-5}$

$\Rightarrow$ shows density variation at (re)-combination

$p + e^{-} \rightarrow H + \gamma$

CMB:

$t = 380.000$ years
$z = 1100$ ; $T \sim 3000K$; $kT \sim 0.3$ eV

$\Rightarrow$ Universe was 1100 times smaller

scale factor:  $R = 1$ today,  $R = 1 / 1100$ at (re)-combination
Dark Matter Search shows the oscillation modes which are at maximum compression or maximum expansion at the time of (re)combination.
did this anisotropy grow to today’s structure?
Structure Formation in the Universe

density $\rho$; pressure $p$, speed $v$, gravity potential $\Phi$

continuity eq.

$$\frac{\partial \rho}{\partial t} + \nabla (\rho \bar{v}) = 0$$

Euler eq.

$$\frac{\partial \bar{v}}{\partial t} + (\bar{v} \nabla) \bar{v} = -\frac{\nabla p}{\rho} - \nabla \Phi$$

Poisson eq.

$$\nabla^2 \Phi = 4\pi G \rho$$

for small disturbance

$$\delta = \frac{\rho_1}{\rho_0} \ll 1$$

“wave eq” with gravity

$$\ddot{\delta} - v_s^2 \nabla^2 \delta = 4\pi G \rho_0 \delta$$

- density only oscillates
- no structure growth as long as pressure term is large

$$v_s^2 = \frac{\partial p}{\partial \rho}$$
Structure Formation in the Universe

density $\rho$; pressure $p$, speed $v$, gravity potential $\Phi$

“wave eq“ with gravity

$$\ddot{\delta} - v_s^2 \nabla^2 \delta = 4\pi G \rho_0 \delta$$

pressure term

$$E = \sqrt{p^2 c^2 + m^2 c^4}$$

pressure comes from kinetic energy

relativistic particles
radiation

$p c \gg m c^2$ $\Rightarrow$ pressure $\neq 0$

non-relativistic particles

$p c \ll m c^2$ $\Rightarrow$ no pressure

no structure growth

- before (re)-combination $p + e^- \Rightarrow H + \gamma$ (cosmic microwave background)

- as long as particles are relativistic $kT > m c^2$
Structure Formation in the Universe

no structure growth

- before (re)-combination \( p + e^- \rightarrow H + \gamma \) (cosmic microwave background)
- as long as particles are relativistic \( kT > mc^2 \)
Structure Formation in the Universe

R: scalefactor if defined = 1 today, was 1/1000 at (re)combination

\[ \frac{\partial^2 \delta}{\partial t^2} - v^2 \Delta \delta = 4\pi G \rho_0 \delta \]

Once density contrast \( \delta \) grows, it grows like the scale factor

\[ \delta \sim R \sim 1/T \]

\[ \Rightarrow \delta \times 1000 \]

Since (re)combination

Today 2.7K – recomb ~ 3000 K
observed anisotropy of $10^{-5}$ by far too small

was there a $100 \times$ larger anisotropy we cannot see in the CMB?

if yes, then made out of particles without electromagnetic interaction

otherwise we would see it in CMB

$\Rightarrow$ Dark Matter
Structure Formation in the Universe

Dark Matter

Baryons (p,n,e⁻, H, He)

(re) combination, CMB

t

the only non electromagnetic particles in the standard model are Neutrinos

**BUT:** Neutrinos still relativistic at (re)combination (kT ~ 0.3 eV) cannot form structure

\[ \omega^2 = v_s^2 k^2 - 4\pi G \rho_0 \]

=> dark matter is made out of beyond SM particles
charged particles (p, e⁻) oscillate in a background non-oscillating gravity field
=> neutral particles, which started structure formation much earlier
=> physics beyond standard model of particle physics
charged particles \((p, e^-)\) oscillate in a background non-oscillating gravity field

\[ \Rightarrow \text{neutral particles, which started structure formation much earlier} \]

\[ \Rightarrow \text{physics beyond standard model of particle physics} \]
Dark Matter Search

- weakly interacting
- heavy ( > ~ keV)

many ideas:
- sterile keV neutrinos
- Axions
- Supersymmetry
- ...

100 GeV - ~ 1000 GeV
mass range is “quite natural“

- accelerator bounds
- thermodynamics during big bang
- Supersymmetry

or ~ 5 GeV

- if it shares matter-antimatter asymmetry
  \[ m_\chi \sim \Omega_{DM} / \Omega_{p,n} * m_p \]

new particles
beyond the standard model

WIMP
weakly interacting massive particle
WIMP direct production at LHC

Large Hadron Collider
CERN - Genf

make it

on land
Dark Matter Search

WIMP over density in earth, sun, galactic center

WIMP indirect search - neutrino telescopes -

search for high energy annihilation products

e.g. high energy neutrinos from sun
Neutrino Teleskope

The Site:
5 cm of Powder, 2 km of Base,
Never Rains, and Lots of Non-stop Sunshine

INECUBE at south pole

ANTARES, KM3Net
In the mediterranean

Neutrino durchdringt die Erde
charged current reaction kurz vor dem Detektor
⇒ aufsteigende Muonen
(nur durch Neutrinos machbar)
⇒ Richtung und Energie des Neutrinos
⇒ Neutrino – Astronomie
WIMP Indirect Search - Neutrino Telescopes -

- ICECUBE at south pole
- AMANDA for planes
- South Pole
- Dome
- Aerial view of South Pole
- SuperK upward muons
- ANTARES, KM3Net
- In the mediterranean
- Upward muons in ice
- Muons in water

Site:
Never Rains, and Lots of Non-stop Sunshine

10 TeV
1 km
WIMP indirect search

\[ \text{gamma-telescopes} \quad \text{and} \quad \text{anti-matter} \]

\( \gamma \)-ray telescopes: \textit{CTA, HESS, MAGIC}, ...

\( \gamma \)-ray satellites: \textit{FERMI}, ...

Search for high energy annihilation products

e.g. high energy gammas from galactic center

\[ \chi + \chi \rightarrow \gamma, \bar{p}, \bar{D}, \ldots \]

Antimatter (Anti-Deuteron)

Searches: \textit{AMS, PAMELA,} ...

in space

\( E_\gamma = 20 \text{ MeV} \rightarrow 300 \text{ GeV} \)

LAT

GBM

\( E_\gamma = 5 \text{ keV} \rightarrow 20 \text{ MeV} \)
WIMP – direct detection by elastic scattering off nuclei
Underground laboratories for rare event searches

WIMP search in the underground

Gran Sasso Labor

shielding
1.5km rock

CRESST experiment
TU München
Max Planck Physik München
Uni Tübingen
WIMP – Direct Detection

Weakly Interacting Massive Particles = WIMPs

Elastic Scattering off Nuclei

• Nuclear Recoils: reduced efficiency for charge- or light-production

- Mass $GeV - \sim 1000 \, GeV$
- relative speed $270 \, km/s$
  ($\sim$ orbital speed in Milky Way)

$\Rightarrow$ only a few keV of energy

- cross section $\sigma_\chi < 10^{-36} \, cm^2$
- local WIMP-Density $\rho_\chi = 0.3 \, GeV / cm^3 - \text{corresp. 3 WIMPs}^{(100 GeV)} / \text{Liter}$
  - 75000 /s /cm$^2$

$\Rightarrow$ very very rare scattering events($< 1 / \text{Week} / \text{kg}$)

Today’s sensitivity $< 1 / \text{year} / \text{kg}$
Particle Identification
by Combination of Channels

cryogenic charge / phonon

radioactive background can be rejected
=> highly improved sensitivity

cryogenic light / phonon

EDELWEISS
CDMS, EURECA

Phonons

Charge

Light

liquid noble gas light / charge

CRESST
EURECA

WARP, ArDM, LUX, ZEPLIN

XENON
Liquid Noble Gases

Background Rejection by Light vs. Charge
Liquid XENON  Charge + Light

**XENON10**  
*2007*  
5.5 kg target,  
58.6 kgd exposure  
10 background events  
~1 cts / 6 kgd

**XENON100**  
*2011*  
34 kg target,  
~2500 kgd exposure  
2 background events  
~1 cts / 1500 kgd, ~1 cts / 4 kg years  
γ bckgrnd ~ 250 x lower

**LUX**  
*2015*  
118 kg target,  
~10000 kgd exposure  
<1 background events  
~1 cts / 25 kg years  
γ bckgrnd ~ again 25 x lower

large improvement on sensitivity
Example: Radio-pure PMTs for XENON1T

Hamamatsu
R11410-21
3”, 248 pcs

- careful material selection,
- screening of materials
- screening of final PMTs
  < 1mBq/PMT in U/Th

Intensive cooperation:
- improvements & optimization
- radio-purity

- extensive testing at room temperature and cold
  high QE: 35% at 175nm
  stability, tightness, …
  30% single PE resolution

JINST 12 P01024 (2017)
$$\leftrightarrow$$ electronic recoil BG from materials
JCAP 04 (2016) 027
Krypton Analytics

unstable $^{85}\text{Kr}$ in air $\rightarrow$ impurity in Xenon gas
- active removal by distillation
- control by precise measurements

Kr measurements:
- with gas chromatography
- Rare Gas Mass Spectroscopy
  (RGMS @MPIK)
  $\rightarrow$ measure $^{nat}\text{Kr}$ to ppt level
  $\rightarrow$ extrapolate: $^{85}\text{Kr}$ from atmospheric abundance
  $\rightarrow$ RGMS down to ppq level

- $^{84}\text{Kr}$ measurement with atomic trap
  (ATTA @ Columbia U)
  $\rightarrow$ measurement of $^{84}\text{Kr}$ to ppt level
  $\rightarrow$ extrapolate: $^{85}\text{Kr}$ from atmospheric abundance
  $\rightarrow$ atom trap operational and efficient for Ar$^*$
Krypton Removal by cryogenic Distillation

- commercial Xenon contains 1 ppm – 10 ppb of Kr
- $^{85}$Kr is unstable

- goal: reduce Kr to sub ppt
- XENON100 achieved $(19 \pm 1)$ ppt

XENON1T distillation column (Münster):
- through-put up to 6.5 kg/hr
- separation factor $> 6.4 \times 10^5$
- final Kr/Xe < 1 ppt
- capable to obtain an output concentration < 48 ppq
- also operated for Rn removal
Direct DM Searches

low WIMP masses:
- low energy threshold
- moderate target masses
- cryogenic detectors

high WIMP masses:
- large targets
- moderate energy threshold
- liquid noble gas (Xenon) detectors

Graph showing the WIMP-nucleon cross section and WIMP mass, with different experiments and their results.
Liquid Noble Gases – (near) future

**XENON** (European, US, ..)
- **XENON100**, 50kg fid vol.
- expect new data
- **XENON 1t** (3,3t in total)
  - running since 2016
  - presently best limits
  - $7.7 \times 10^{-47}$ cm$^2$ @ 35 GeV

**LUX + ZEPLIN: LZ** (US, European, ..)
- 7t Xe approved by NSF & DoE

**Dark Side @ LNGS** (Italy, US, ..)
- funded: 1 t depleted LAr

**DEAP** (Canada, US, ..)
- 1-phase, SNOLAB
- 1000 kg fid. running
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Direct DM Searches

**low WIMP masses:**
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- large targets
- moderate energy threshold
- liquid noble gas (Xenon) detectors
Cryogenic Experiments

Phonon + Light or Phonon + Charge

CRESST II - Detectors
simultaneous Light and Phonon

Thermometer

Absorber CaWO₄
Phonon-Detector
reflecting foil

CRESST
Cryogenic Rare Event Search with Superconducting Thermometers

Max-Planck-Institut München, TU München
Universität Tübingen, Oxford University, Gran Sasso
Cryogenic Experiments

**SuperCDMS**
*Cryogenic Dark Matter Search*
US Kollaboration

**Charge + Phonon**
*(semiconductor Ge, Si)*

**EDELWEISS**
*Experience pour DÉtecter Les Wimps En Slte Souterrain*
France and Germany

**Charge + Phonon**
*(semiconductor Ge)*

**CRESST**
*Cryogenic Rare Event Search with Superconducting Thermometers*

*Max-Planck-Institut München, TU München*
*Universität Tübingen, Oxford University, Gran Sasso*
Cryogenic Experiments: Phonon + Light or Phonon + Charge

- calorimeter arrays
- module masses 20g – 1400g
- thermometers: superconducting phase transition or highly doped semiconductors
- low energy threshold => good at low WIMP masses

SuperCDMS
- approved by NSF & DOE at SNOLAB
- installation for 400kg target
- present funding for 50kg
- start ~ 2020

EDELWEISS
- 36 x 800g Ge detectors at LSM

CRESST
- 18 x 300g CaWO₄ detectors at LNGS
- since 2016 10 x 24 g
  ⇒ lower threshold
  ⇒ even better at low WIMP mass
  lowest threshold leading at low WIMP masses
Cryogenic Experiments

- SuperCDMS @ SNOLab approved by NSF & DOE, ~2020
- presently CRESST leading at low WIMP masses
- probe higher WIMP masses in case of a positive detection with a multi element target CaWO$_4$, Ge, Si, …
- potential to reach solar neutrino sensitivity
Direct Dark Matter Search – (near) future

1t scale liquid Xenon detectors running
XENON 1t
LZ coming

Cryogenics:
EDELWEISS and CRESST continue running
SuperCDMS funded
worldwide cooperation

- sensitivity at low and high WIMP masses will improve
- in case of discovery: good possibilities for multitarget confirmation
- might turn into neutrino detection
LHC DM Searches

**ATLAS**
$s=13$ TeV, 36.1 fb$^{-1}$
Exclusion at 90% CL
Vector mediator
Dirac DM
$g_q=0.25$, $g_\chi=1$

**ATLAS**
$s=13$ TeV, 36.1 fb$^{-1}$
Exclusion at 90% CL
Axial-vector mediator
Dirac DM
$g_q=0.25$, $g_\chi=1$

**Equation:**

$$\sigma_{SI}(\chi\text{-nucleon}) [\text{cm}^2]$$

**Legend:**
- Observed
- PandaX
- LUX
- CRESST-II
- CDMSlite

**Equation:**

$$\sigma_{SD}(\chi\text{-proton}) [\text{cm}^2]$$

**Legend:**
- Observed
- PICO-60
- LUX
IceCube (indirect) DM Searches

spin dependent interaction
there are 336 neutrinos / cm$^{-3}$ left from Big Bang

⇒ could be a considerable contribution to Dark Matter

$$\sum_{i=1}^{3} m_{\nu_i} \sim 10 \text{ eV}$$

100% of dark matter if
Neutrinos

the only non electromagnetic particles in the standard model are Neutrinos

**BUT:** Neutrinos still relativistic at (re)combination (kT ~ 0.3 eV) cannot form structure

\[ \omega^2 = \nu_s^2 k^2 - 4\pi G Q_0 \]
Neutrinos

there are 336 neutrinos / cm$^{-3}$ left from Big Bang

⇒ could be a considerable contribution to Dark Matter

$100\%$ of dark matter if $\sum_{i=1}^{3} m_{\nu_i} \sim 10$ eV

but: they are too light

⇒ look at structure in the Universe to get limits on $\sum_{i=1}^{3} m_{\nu_i}$
Neutrinos
Neutrinos

\[ \Omega_{\text{matter}} \sim 0.30 \]
\[ \Omega_{\nu} < 0.02 \]

Why not Neutrinos?

\[ \Sigma m_{\nu_i} < 0.6 \text{ eV} \]
‘Standardmodel’ of Cosmology

Dark Energy \( \Omega_{\text{vac}} = 73 \% \)

Dark Matter \( \Omega_{\text{mat}} = 23 \% \)

normal Matter \( \Omega_{\text{mat}} = 4\% \)

---

Standardmodel of Particle Physics

expected from Standardmodel

\( 0 \text{ or } 10^{120} \)

possible explanations beyond the Standardmodel

\( 0 \text{ or } 10^{55} - 120 \)

\( 0 \% \)

\( 0.1 - 2 \% \)

\( 0 \% \)

\( \text{may be} 4 \% \)

\( 0 \% \text{ or } 10^{120} \)

4-6 \%

\( \Rightarrow \text{Physics beyond the Standardmodel} \)

\( \Rightarrow \text{at least one of the ‘standards’ has to be changed (most likely both)} \)

\( \Rightarrow \text{(direct) Dark Matter search is testing both} \)

\( \Rightarrow \text{exciting times} \)