Direct Dark Matter Searches

Manfred Lindner

CosPA 2016
8 Nov. to 2 Dec. 2016
Sydney, Australia
A long List of Evidences ...

+ Galactic rotation curves
+ Galaxy clusters & GR lensing
+ Bullet Cluster
+ Velocity dispersions of galaxies
+ Cosmic microwave background
+ Sky Surveys and Baryon Acoustic Oscillations
+ Type Ia supernovae distance measurements
+ Big Bang Nucleosynthesis (BBN)
+ Lyman-alpha forest
+ Structure formation
+ …

⇒ Strong indirect evidence for a large dark sector
⇒ dynamic, static, radiation, …
⇒ cannot be explained by ordinary matter
The cosmic Matter Balance

- Dark matter: 26.8%
- Dark energy: 68.3%
- Stars: 0.8%
- H & He: gas 4%
- Radiation: 0.005%

Important:
- One component?
- Mixture?
- Direct detection of DM!

Neutrinos = CvB:
- $\nu_e$: 0.17%
- $\nu_\mu$: 0.17%
- $\nu_\tau$: 0.17%

Something invisible in addition to CvB

Direct detection of DM!
# Competing Dark Matter Directions

**Gravity**

- **MOND**
  - simple one scale modification
  - → fails badly

- Other GR modifications
  - or
  - a suitable population (mass, number) of black holes

**Particles**

- **BSM motivated** (SM problems)
  - axions
  - sterile $\nu$'s
  - many other particles
  - ...

- **Abundance or model motivated**
  - various candidates
  - ...

**WIMPs** combine both aspects in an attractive way + WIMP miracle
Black Holes as Dark Matter

Marco Cirelli (2016)

MACHO or PBH mass $M$ in solar masses

$10^{-20}$ $10^{-15}$ $10^{-10}$ $10^{-5}$ $1$ $10^5$ $10^{10}$ $10^{15}$

1

$10^{-1}$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$10^{15}$ $10^{20}$ $10^{25}$ $10^{30}$ $10^{35}$ $10^{40}$ $10^{45}$ $10^{50}$

fraction $f$ of DM

PBH evaporated by now

evaporation today

GRB lens

NS in GloC

microlensing

radio lensing

halo binaries

accumulation in GC

X-rays spoil CMB

disfavored by galaxy sizes

moon
Is it Particles?

• bullet cluster (1E 0657-56)
  - colliding galaxy clusters
    = stars, gas, DM ; up to $10^6$ km/h
  - x-rays from charged particle interactions
  - Dark Matter just traverses w/o scattering
    ➔ displacement of
    visible matter
    and
    GR potential = all matter
    ➔ effect is $\sim 8\sigma$

• Shows that normal particles scatter, but NOT that DM is particles
Hierarchy Problem $\Rightarrow$ MSSM $\Rightarrow$ DM

- LSP=Neutralino $\Rightarrow$ WIMP miracle $\Rightarrow$ correct abundance

Scan parameter space for different annihilation channels $\Rightarrow \Omega h^2$

Note again: we will not argue for equal probability in parameter space!

$\tilde{\chi}_1^0 \tilde{\ell}$ coannihilation
$\tilde{\chi}_1^0 \tilde{\chi}_1^+$ coannihilation
$t\bar{t}$
$W^+W^-$
$q\bar{q}$
$\ell\bar{\ell}$

$\Rightarrow$ Select correct range of $\Omega h^2$ $\Rightarrow$ constrains parameter ranges
How fine-tuned are the parameters?

- **MSSM neutralino: Level of fine-tuning \( \Delta_{\text{tot}} \)

\[
\Delta p_i = \left| \frac{p_i}{M_Z^2} \frac{\partial M_Z^2(p_i)}{\partial p_i} \right| = \left| \frac{\partial \ln M_Z^2(p_i)}{\partial \ln p_i} \right|
\]

\[
\Delta_{\text{tot}} = \sqrt{\sum_{p_i=\mu^2, b, m_{H_u}, m_{H_d}} \{ \Delta p_i \}^2}
\]

\[
\rightarrow \text{XENON100-2010}
\]

\[
\rightarrow \text{XENON100-2012}
\]

\[
\rightarrow \text{XENON1T}
\]

- **XENON100 cuts already into expected space**
- **XENON1T covers a much larger part**
  * XENONnT covers most
  \( \Rightarrow \) high potential
  \( \Rightarrow \) be first!

**LMSSM: x-section down**

Grothaus, ML, Takanishi: **full** MSSM, not cMSSM, pMSSM, NMSSM… \( \Leftrightarrow \Rightarrow \) WIMP miracle?
Generic WIMP Crosssection

- **Quantum mechanics**: wavelength $\lambda \sim 1/\text{mass}$
- "**size/area**" of a particle: $\pi \lambda^2 = \pi/m^2$
- **scattering crosssection** = area times coupling strength

$$\sigma \sim O(0.001-1.0)^2 g_s^2 \pi/m^2$$ or tuning, symmetry, …

- model parameters
- weak area
- coupling

$\Rightarrow$ the natural / expected range for a 50GeV WIMP:

$$\sigma \sim 10^{-42} - 10^{-48} \text{ cm}^2$$

known amount of DM $\Rightarrow \sim \text{WIMP flux} \Rightarrow \text{event rate}$

$\Rightarrow$ we know size/sensitivity of a detector which can cover the most interesting natural WIMP space
Generic WIMP parameter space will be covered in the next years
Systematically lowering the x-section (symmetry, tuning,...)? ←→ WIMP miracle?
Hunting WIMPS in different Ways

known Standard Model (SM) particles interact with WIMPs: assumptions...

indirect detection

fermi, pAMELA, AMS, HESS, icecube, ...
astronomical uncertainties...
→ signal without doubt from DM?
keV lines ↔ atomic physics

direct detection

WIMP wind: 220 km/s from Cygnus
→ modelling

Colliders

may detect new particles, but is it DM (lifetime, abundance)?
ICHEP2016: Nothing seen...
→ impact on theory...
→ SUSY → higher scale
→ other SB motivated WIMPs
→ new ideas/candidates

M. Lindner MPIK
keV Lines, Hitomi & Charge Exchange Reactions

Hitomi X-ray satellite (failed March 26, 2016)
Before: look at the Perseus galaxy cluster @232Mly
→ no sign of the previously reported X-rays

Charge exchange explanation of 3.5 keV line
Highly charged ions in and between galaxies
→ completely ionized sulfur (S^{16+})

(S^{16+}) coming close to H
→ charge exchange reaction → excited (S^{15+})
→ de-excitation by emission of 3.5 keV photon
→ 3.5 keV gamma line…

Intensity ↔ fits typical abundance
→ 3.5 keV lines not from dark matter

lesson: there may be other keV lines …
… and other charge exchange reactions
→ unambiguous detection is difficult
Different direct Detection Techniques

- 1% energy: fast response, no surface effects
- 10% energy: fast response
- 100% energy: slowest response
- Cryogenics

- WIMP (Weakly Interacting Massive Particles)
- Ionization
- Heat
- Light

Materials:
- Ge
- Ge, Si
- Al$_2$O$_3$, LiF
- CaWO$_4$, BGO
Different direct Detection Techniques

Detection methods: Crystals (NaI, Ge, Si), Cryogenic Detectors, Liquid Noble Gases

- CoGeNT, CDEX, Texono, Malbek, DAMIC
- XENON, LUX/LZ, ArDM, PandaX, Darkside, DARWIN
- SuperCDMS EDELWEISS
- DEAP3600, CLEAN, DAMA, KIMS, XMASS, DM-Ice, ANAIS, SABRE
- CRESST
- CRESST-I CUORE
- Tracking: DRIFT, DMTPC MIMAC, NEWAGE
- Superheated Liquids: COUPP, PICO, PICASSO, SIMPLE

Detection methods:

- Light
- Heat
- Ionization
Light WIMPs: SuperCDMS - EDELWEISS - CRESST

**SuperCDMS @SNOLAB**
Aim: 50 kg-scale (cryostat up to 400kg) low threshold, less bg: deeper, cleaner, upgraded electronics, data taking 2020+

**EDELWEISS @LSM**
2016: 20 kg Ge array
2017: 350 kgd in HV mode
optimize 1-10 GeV sensitivity
future: ton scale together with CDMS (EURECA) +GeMMC

**CRESST @LNGS**
2013-2015, 52 kg × d
now: best threshold 300 eV\textsubscript{nr}
excellent sensitivity for small WIMP mass

---

**EDELWEISS-III results \_2016**

**EDW-III goals 2017**

35 ton-days

**SuperCDMS@SNOLAB**

---

**CRESST-III Phase 1**

---
DEAP-3600 @ SNOLAB

- Single phase LAr TPC, 3.6t (1t fiducial)
- Spherical ultra pure acrylic vessel
- 255 PMTs, extra shielding (foam, PE)
- TPB wavelength shifter → 128nm scintillation light into visible light
- Water tank + veto PMTs
- Ready for physics run ~filled → physics run
Dual Phase TPCs: XENON100, LUX, PandaX

Recent Results
Improvement of SI limit with respect to Run II by a factor of $1.7 \times 50 \text{ GeV/c}^2$ and $1.09 \times 10^{-45} \text{ cm}^2$

…while we were building XENON1T…
Belli IDM 2016

DAMA/Libra phase 2 is running

9.2 $\sigma \rightarrow$?
Incompatible with other Results

• Spin-independent interactions Standard halo model
• Spin dependent
In addition: New NaI Projects to directly test DAMA ➔ clarify the modulation signal
SABRE@LNGS, COSINE-100 (DM-Ice+KIMS) @Yangyang, ANAIS @Canfranc

Conclusion: Leptophilic models excluded; annual modulation must have another origin *or* sophisticated models with a signal in DAMA and nowhere else
arXiv:1608.07648

Both LUX runs combined

3.35 \times 10^4 \text{ kg-day exposure}

At m_{\text{WIMP}} = 50 \text{ GeV}:

2.2 \times 10^{-46} \text{ cm}^2 @90\%\text{CL}
PhysRevLett.116.161302

95 live days ($1.4 \times 10^4$ kg·days)
PandaX: SI Result

Results from 98.7 days of PandaX-II

arXiv:1607.07400
arXiv:1611.06553

exposure of $3.3 \times 10^4$ kg-day

most stringent limits above 10 GeV/c$^2$

+ limits from LHC for low WIMP masses.
Meanwhile: Construction of XENON1T

- plan: x100 compared to XENON100
- target/Detector: 3.5t LXe TPC with 250 high QE low radioactivity PMTs
- water Cherenkov muon veto
- cryogenics: Xe cooling / purification / distillation / storage systems designed to handle up to 10t of LXe ➔ allows fast upgrade to XENONnT (2018) ➔ another factor x10
- status:
  - all systems successfully tested
  - data taking starts ~ now
- goal: 2x $10^{-47}$ cm$^2$
  @50 GeV for 2ty
The XENON1T inner Detector

- Space for XENONnT TPC; otherwise designed for nT larger - significantly stronger requirements for radiopurity / backgrounds
Extremely sensitive Material $\gamma$-Screening

- Different screening stations@MPIK underground lab (1mBq/kg)
- 4 GEMPIs of MPIK @LNGS (10$\mu$Bq/kg)
- New: GIOVE @MPIK (50$\mu$Bq/kg)

→ extensive task for GERDA, XENON and other experiments
Rn Emanation: avoid $^{222}$Rn ($\alpha$-decaying)

He carrier gas

miniature proportional counters @MPIK

Very clean: bgd for $^{222}$Rn: ~1 ct/day
Gas counting systems @LNGS and @MPIK

$^{222}$Rn emanation technique:
- sensitivity = few atoms/probe
- large samples $\leftrightarrow$ absolute sensitivity
- non-trivial; not commonly available; routine @MPIK
- established numbers:
  - Nylon (Borexino) $< 1 \mu$Bq/m$^2$
  - Copper (Gerda): $2 \mu$Bq/m$^2$
  - Stainless steel (Borexino): $5 \mu$Bq/m$^2$
  - Titanium: $(100 \pm 30) \mu$Bq/m$^2$

- Auto-Ema: New automated Rn screening facility at MPIK $\Rightarrow$ many samples
Krypton Removal

- Cryogenic distillation
- Reduce ppb Kr traces in Xe gas to ppt
- proven technique, achieved (19 +/- 1) ppt in XENON100

**Design Parameters for XENON1T**
- throughput: 3 kg/hr
- factor of $10^4$-$10^5$ separation
- final Kr/Xe < 1 ppt

---

**Münster for XENON1T**
Krypton Analysis

• Kr measurements with gas chromatography plus Rare Gas Mass Spectroscopy RGMS
  → measurement of natKr to ppt level
  → extrapolation to 85Kr from atmospheric abundance
  → gas chromatography: Xe separation
  → demonstrated for XENON100

• 84Kr measurement with atomic trap ATTA
  → measurement of 84Kr to ppt level
  → extrapolation to 85Kr from atmospheric abundance
  → Atom trap operational and efficient for Ar*
  → First Kr/Xe measurements for XENON100 by Fall 2012

MPIK (RGMS): ppt ... ppq sensitivity achieved
Columbia U (ATTA)
used for XENON100 and XENON1T
A lot of Work: E.g PMTs...

- Design, simulation, testing, ... screening $\leftrightarrow$ R&D

Radiopurity optimization of PMTs together with Hamamatsu

Material advice and control with screening for every little piece achieved $< 1 \text{mBq/PMT}$ in U/Th


Extensive tests of PMTs at room temperature and cryogen high QE, stability, tightness, ...

$\rightarrow$ paper to appear very soon

Electronic recoil BG from materials

and then

\[ \rightarrow 20\text{ty} \]

\[ \rightarrow x10 \]

is built while

XENON1T is running;

reuses most parts \( \rightarrow \text{faster} \)
The XENON-Program @ LNGS

XENON1T

3.5 t LXe
commissioning at LNGS

XENONnT

7.5 t LXe
Design stage

XENON100

2008-2016

PRL100
PRL101
PRD 80
NIM A 601

2005-2007

PRL105
PRL109
PRL111, etc

2013-2018

2018-2020

0.95m
0.96m
1.3 m
1.35 m

M. Lindner MPIK
LUX-ZEPLIN (LZ)

- Turning on by 2020 with 1,000 initial live-days plan
- 10 tons total, 7 tons active, ~5.6 ton fiducial
- Unique triple veto
- GOALS: < 2 x 10^{-48} cm², at 40 GeV ~100 times better than LUX
About 25 days of XENON1T data will be enough to catch up and then move on in the remaining generic WIMP parameter space.
Conclusions

Direct detection of Dark Matter is the crucial test to prove that the Universe is full of new particles

- Clear evidence exists for DM in the Universe
- Different options/candidates
  - WIMPs seem best motivated (don’t forget others)
- Excellent opportunity to find or exclude WIMPs in the next years in the favoured / natural parameter space
  - WIMPs might be found or get under pressure
  - in any case exciting progress ahead!