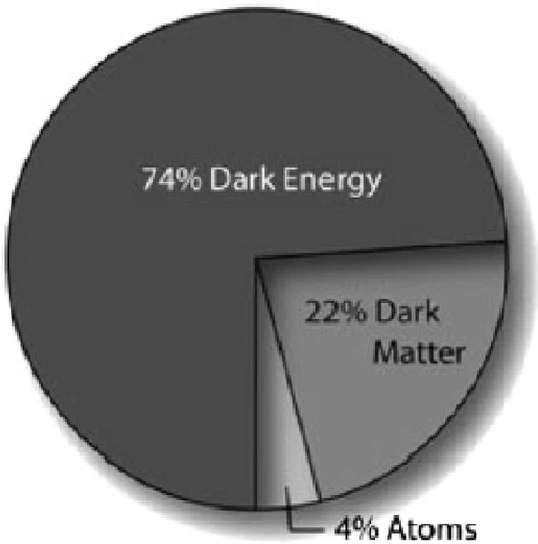
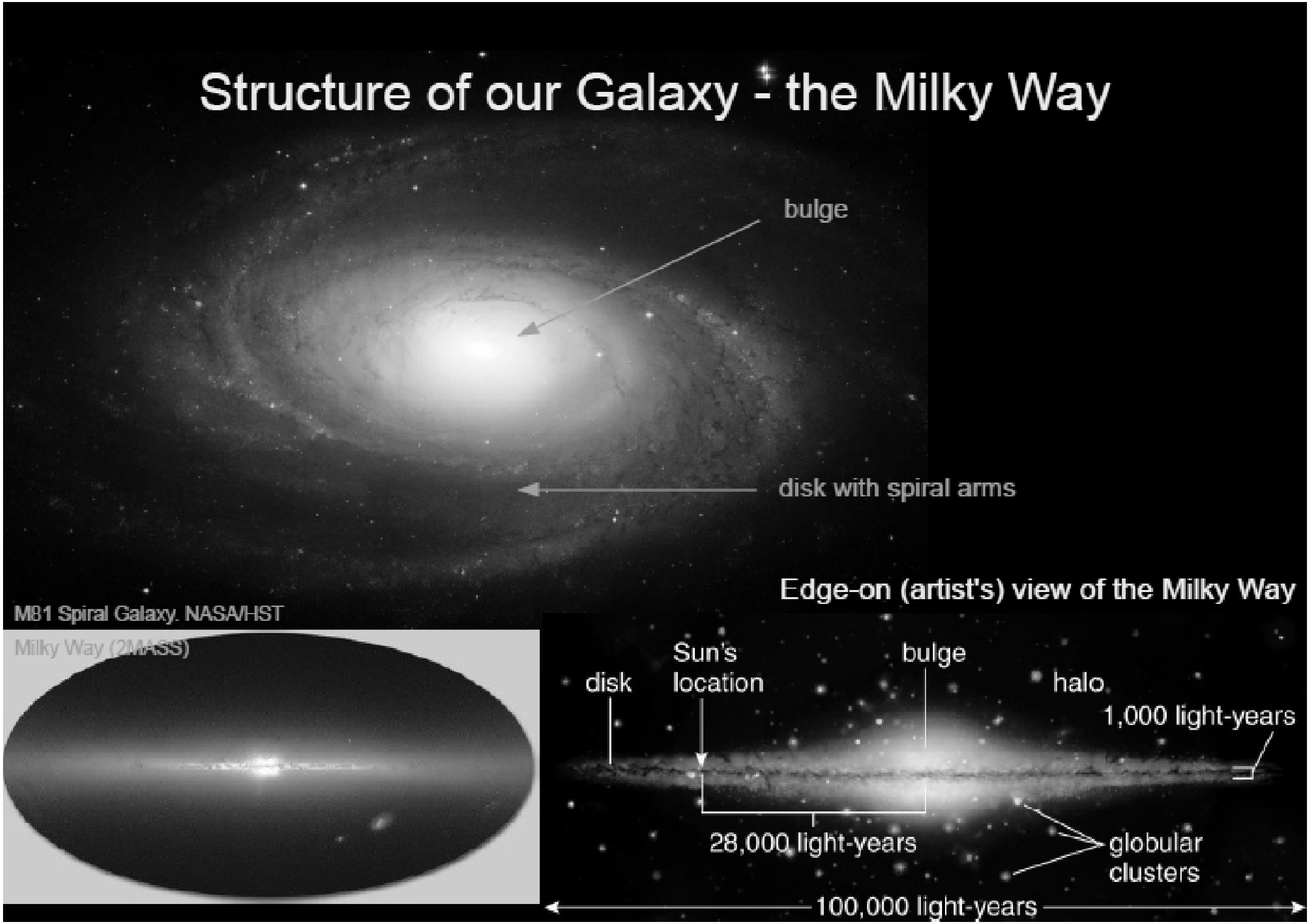
10. Dark matter Searches

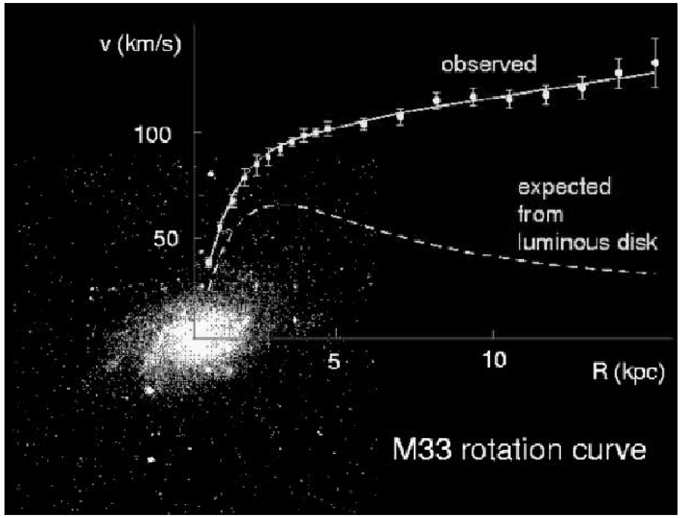



Structure of our Galaxy - the Milky Way
bulge
disk with spiral arms
M81 Spiral Galaxy. NASA/HST
Milky Way (2MASS)
Edge-on (artist's) view of the Milky Way
disk
Sun's location
bulge
halo
1,000 light-years
28,000 light-years
globular clusters
100,000 light-years

- Starting from 1933, when the astronomer Zwicky realized that the mass of the luminous matter in the Coma cluster was much smaller than its total mass implied by the motion of cluster member galaxies:

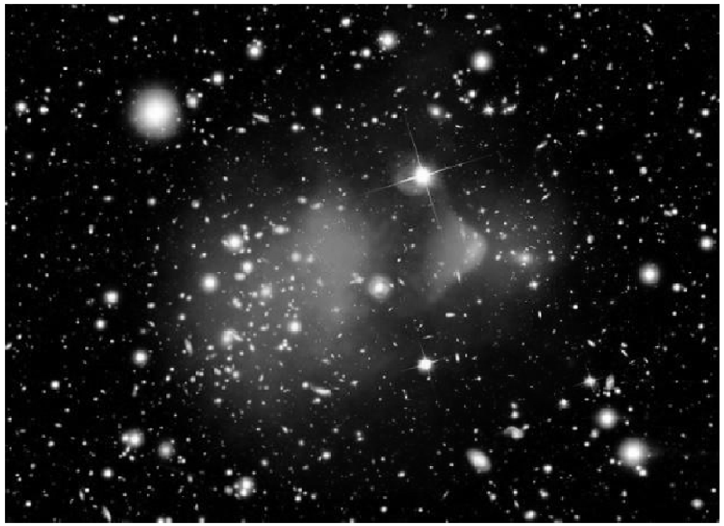
Evidences

Rotation curves of galaxies

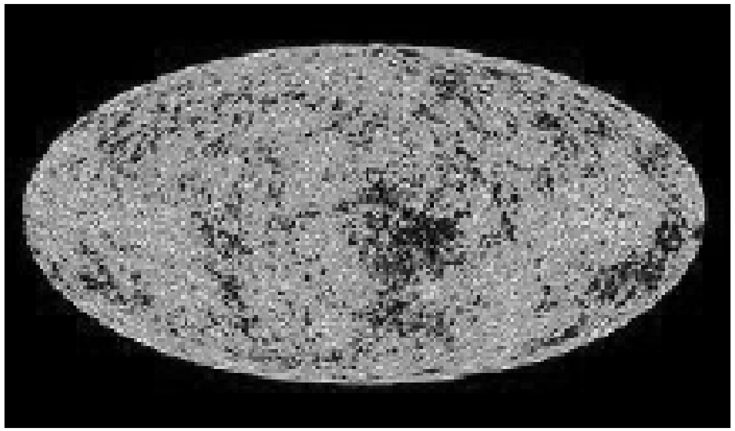


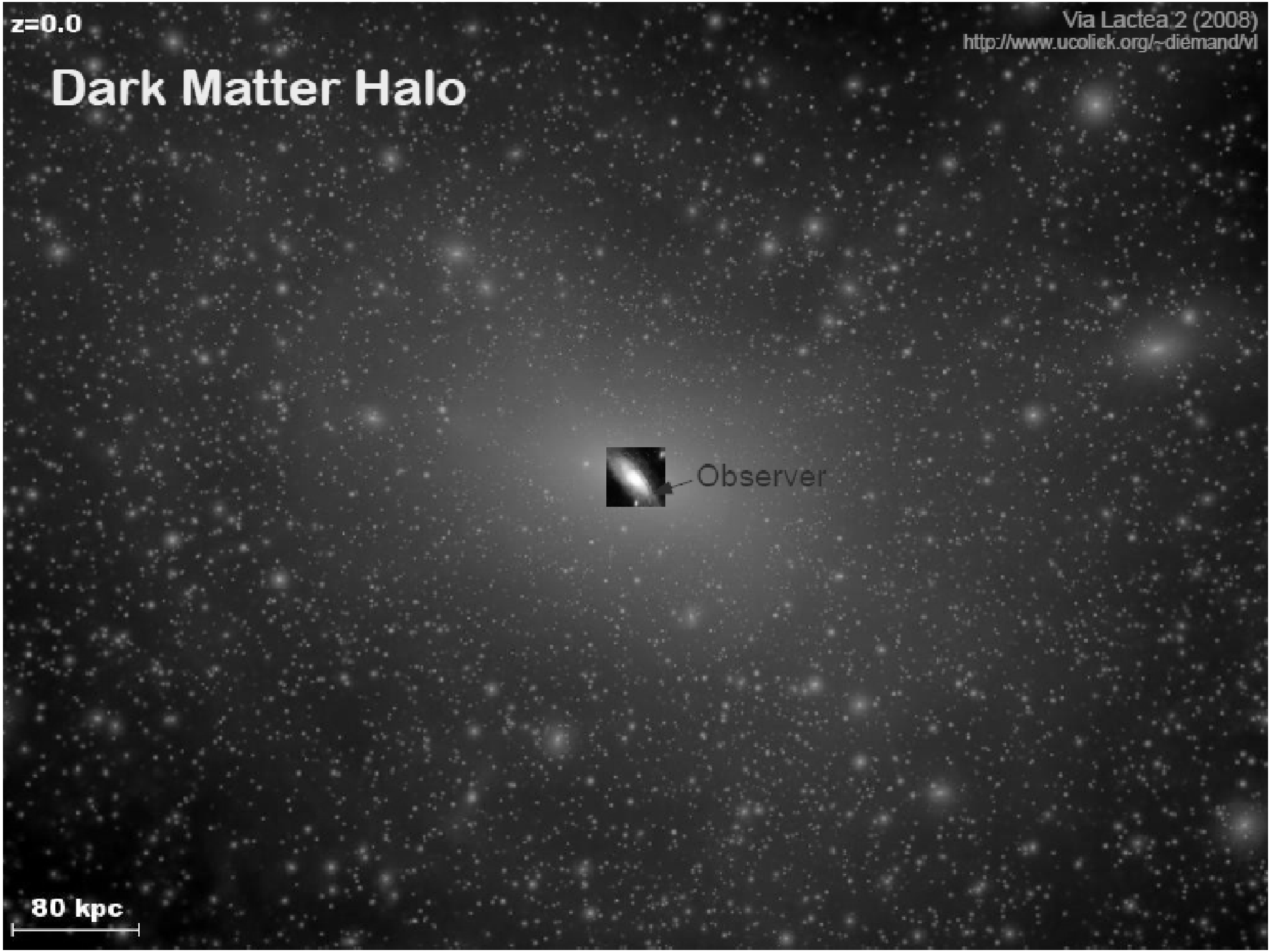
Gravitational lensing

Bullet cluster



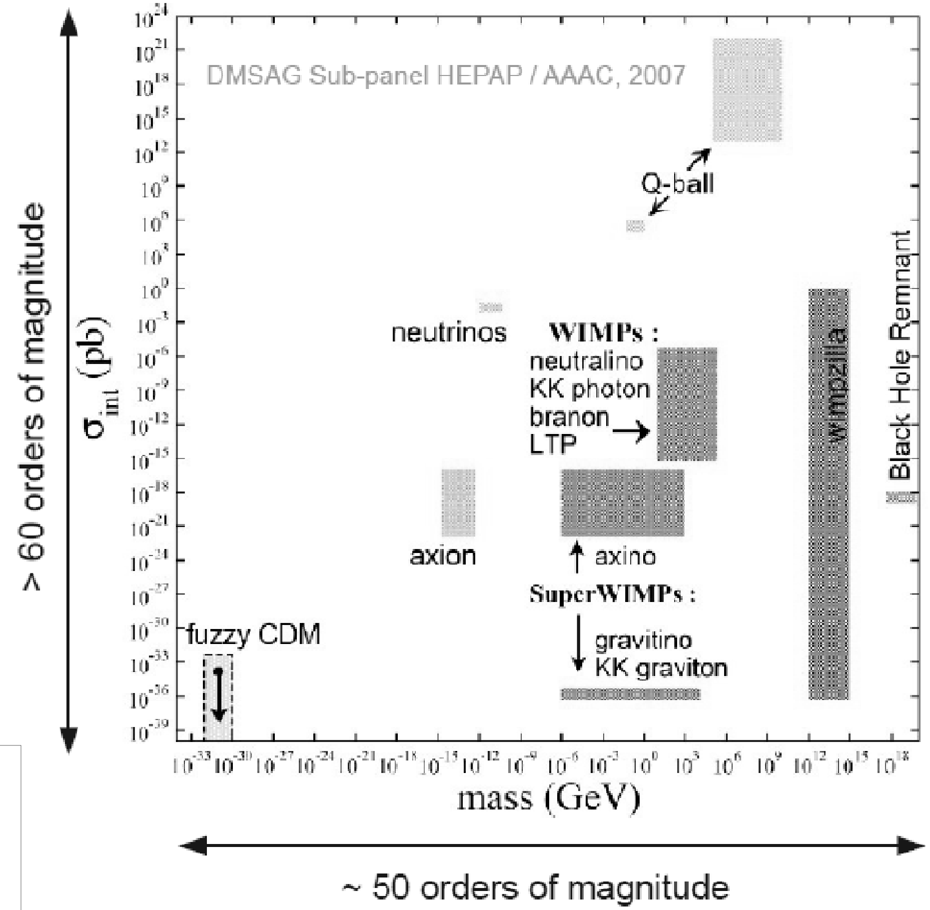
Structure formation as deduced from CMB




z=0.0
Via Lactea 2 (2008)
http://www.ucolick.org/~diemand/vl
Dark Matter Halo
Observer
80 kpc

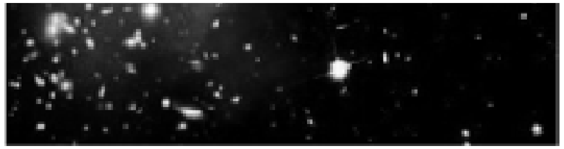
W10.1 What do we know about Dark Matter?

- Gravitationally interacting
  - How we know about Dark Matter
- Stable or long-lived
  - $\Omega_{DM} = 0.23$
- Cold or warm - not hot (relativistic)
  - Structure formation, CMB
- Non-baryonic
  - CMB, Big Bang nucleosynthesis
- Electrically neutral
  - Dark Matter

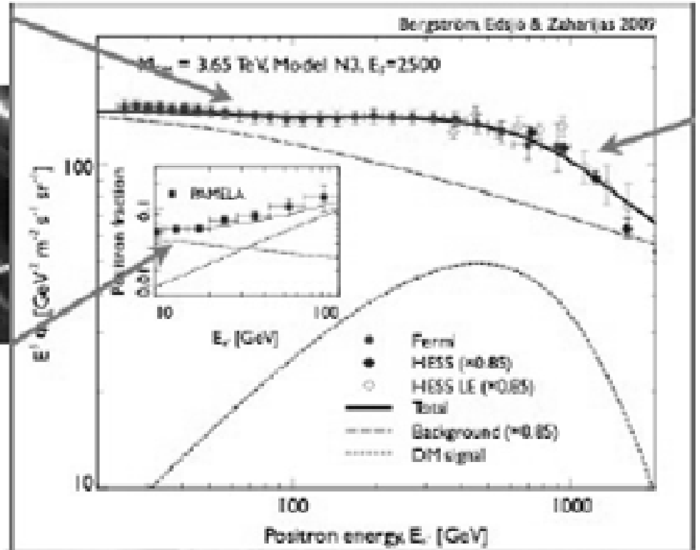


■**Dark Matter requires physics beyond the Standard Model**

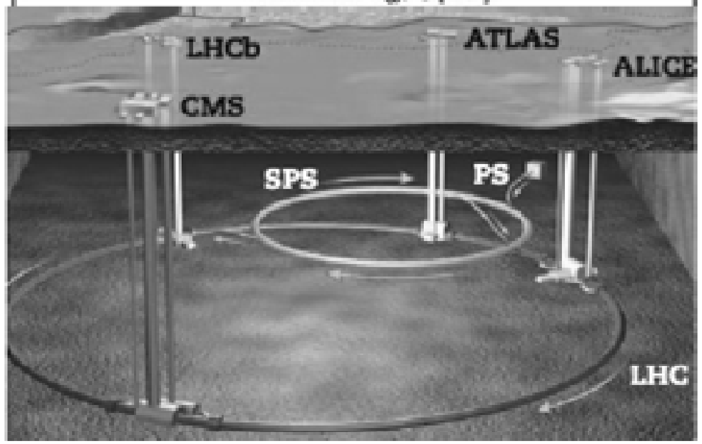
10.2 DM Detection Methods



- Astrophysics / Cosmology:
  Measurement of Gravitational Effects.
  - Rotation curves of spiral galaxies
  - Orbital velocities of galaxies in clusters (Zwicky 1933)
  - Colliding clusters (Bullet cluster)
  - Large scale structure, lensing
- Direct Detection:
  - **WIMP scattering**
  - Axion searches, ...



- Indirect Detection: from annihilation or decay
  - Cosmic rays
    PAMELA positrons?
    Fermi, ATIC, HESS electrons? Anti-deuterons?
  - Neutrinos
  - Gamma-rays
- Accelerator-based Creation and Measurement:
  - Missing energy / momentum (+ jets + lepton(s))
  - Search for (possibly) DM-related particles
    (SUSY, extra dimensions, dark photon)

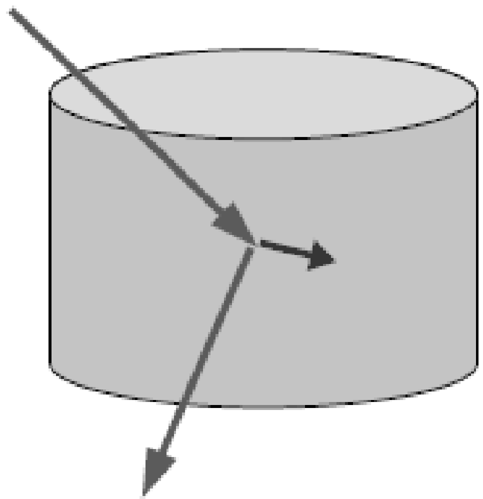


WIMP Dark Matter Direct Detection

- WIMPs χ scatter off of a nucleus with mass m_χ (given by atomic mass A) elastically.
- Nucleus recoils with energy:

$$E_R = 4\frac{m_\chi m_n}{(m_\chi + m_n)^2} E_\chi \cos^2\theta$$

Laboratory system

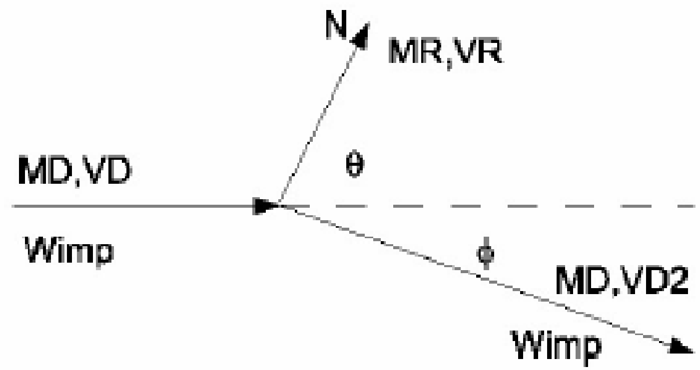


$$E_{R,max} = 4\frac{m_\chi m_n}{(m_\chi + m_n)^2} E_\chi = 2\frac{\mu^2}{m_\chi} v^2$$

$$v_{min} = \left(\frac{m_\chi E_{th}}{2\mu^2}\right)^{1/2}$$

min. velocity to produce signal above threshold

$\mu = (m_\chi m_n)/(m_\chi + m_n)$



- Example:
  - m_χ ~ 10 GeV/c², m_n = 135 GeV/c²
  - v ~ 230 km/s, β = 7.7e-4
  - E_χ = 29.4 keV, $E_{R,max}$ = 7.5 keV

WIMP Dark Matter Direct Detection

- Direct detection methods look for interaction of DM particles in deep underground detectors. DM is expected to interact only with weak coupling, thus easily penetrate through the ground.
- Background: other CR particles (a part the ν), will be stopped.
- The **detectors** are typically filled with target nuclei of iodine, germanium, xenon, silicon. These detectors are sensitive in observing weakly interacting particles that recoil off the nuclei.
- DM particles must be heavy enough to affect the nuclei and direct detection is typically in search of WIMP. The dark matter particle, χ, is expected to interact with the quarks in the nuclei.
- If one assumes that WIMPs make up our Galaxy's halo [$\rho = 0.3 (\mathrm{GeV}/c^2)/\mathrm{cm}^{-3}$], then the local **spatial density** would be $\mathbf{n_\chi \sim 0.003\ (M\chi\ /100\ GeV)^{-1} cm^{-3}}$

■WIMPs would be moving with **velocity v ~ 200 km/s** (Earth is rotating with the Sun in our Galaxy!)

■A typical WIMP cross-section for elastic scattering off quarks for, say, the neutralino is $\sigma \sim 10^{-41\div36}$cm^2.

■The interaction rate is then (for a 100 MeV WIMP):

$$\mathbf{R \sim n_\chi \sigma\, v \sim (0.004\ cm^{-3})(10^{-36}\ cm^2)(2 \times 10^7\ cm/s) \sim 10^{-24}\ yr^{-1}}$$

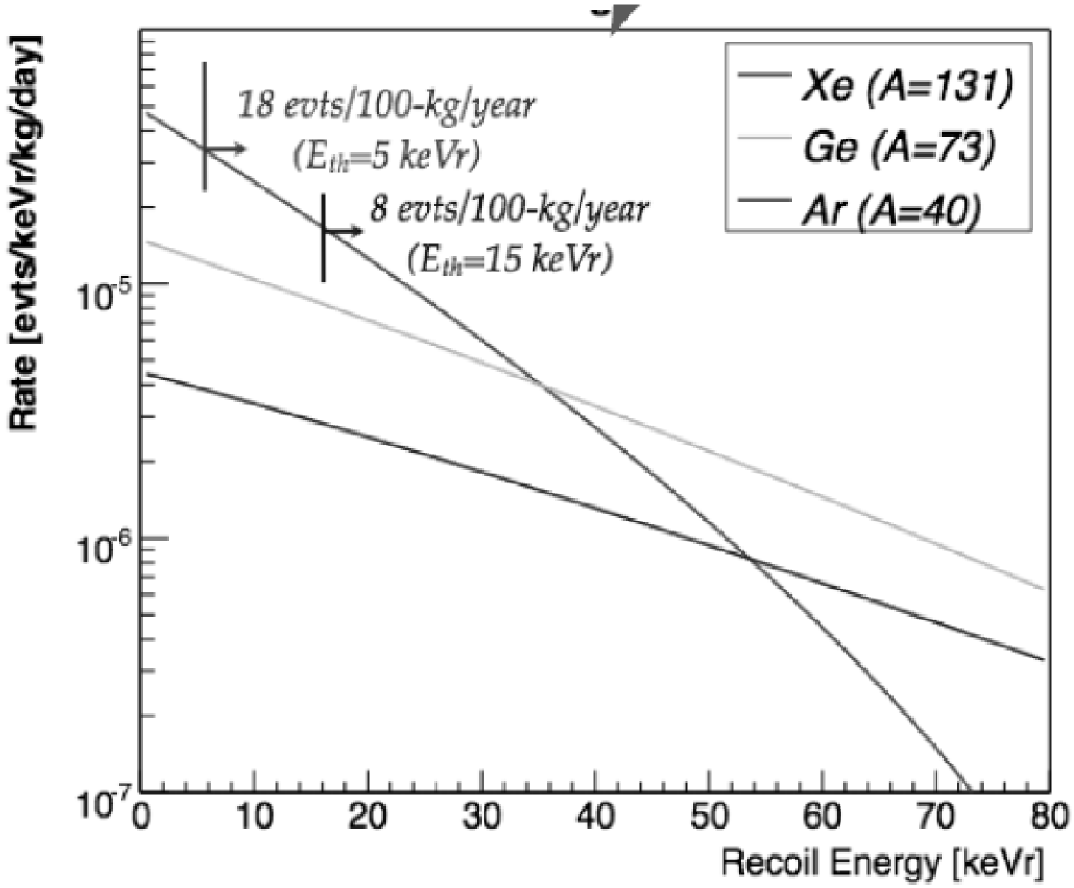
■ If there are 10^{23}M/(Ag) nuclei in the detector, then say for A ~ 100, one expects ***R ~ 0.01-1/kg/yr*** **,** one event per year per kilogram of the detector material.

■ There are two types of expected interactions of the WIMP with the nuclei, **axial and scalar**. These are often referred to as the **spin-dependent** and **spin-independent** interactions, respectively.

■Experimental results are expressed in terms of an **exclusion plot**

- These exclusion plots are usually less constraining both at low WIMP mass, due to the low recoil energy, and at high WIMP mass, because the number density decreases as $n_\chi \sim 1/M_\chi$.
- There are many types of direct search detectors, with the active detector types ranging from scintillator, semiconductors and noble liquids.

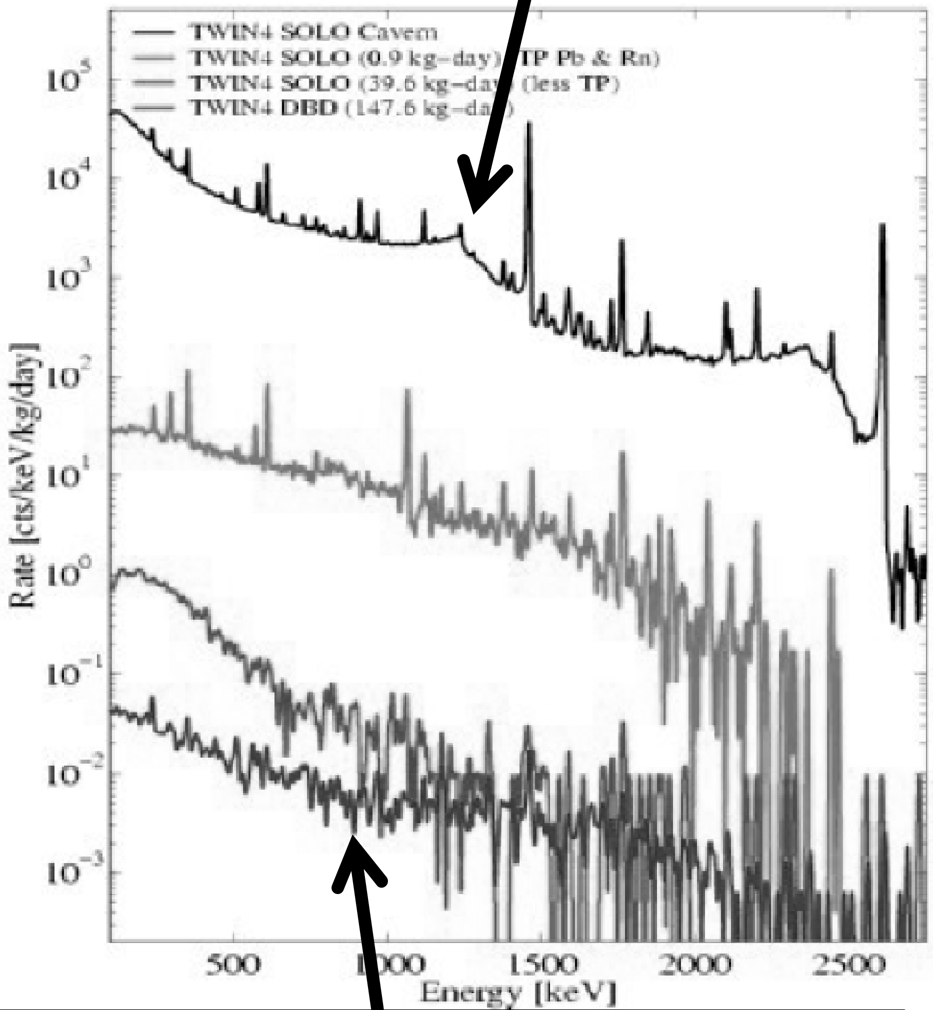
■Dark matter WIMP particles entering the detector on occasion will elastic scatter with the nuclei of the detector, causing it to recoil, with the recoil energy measured.



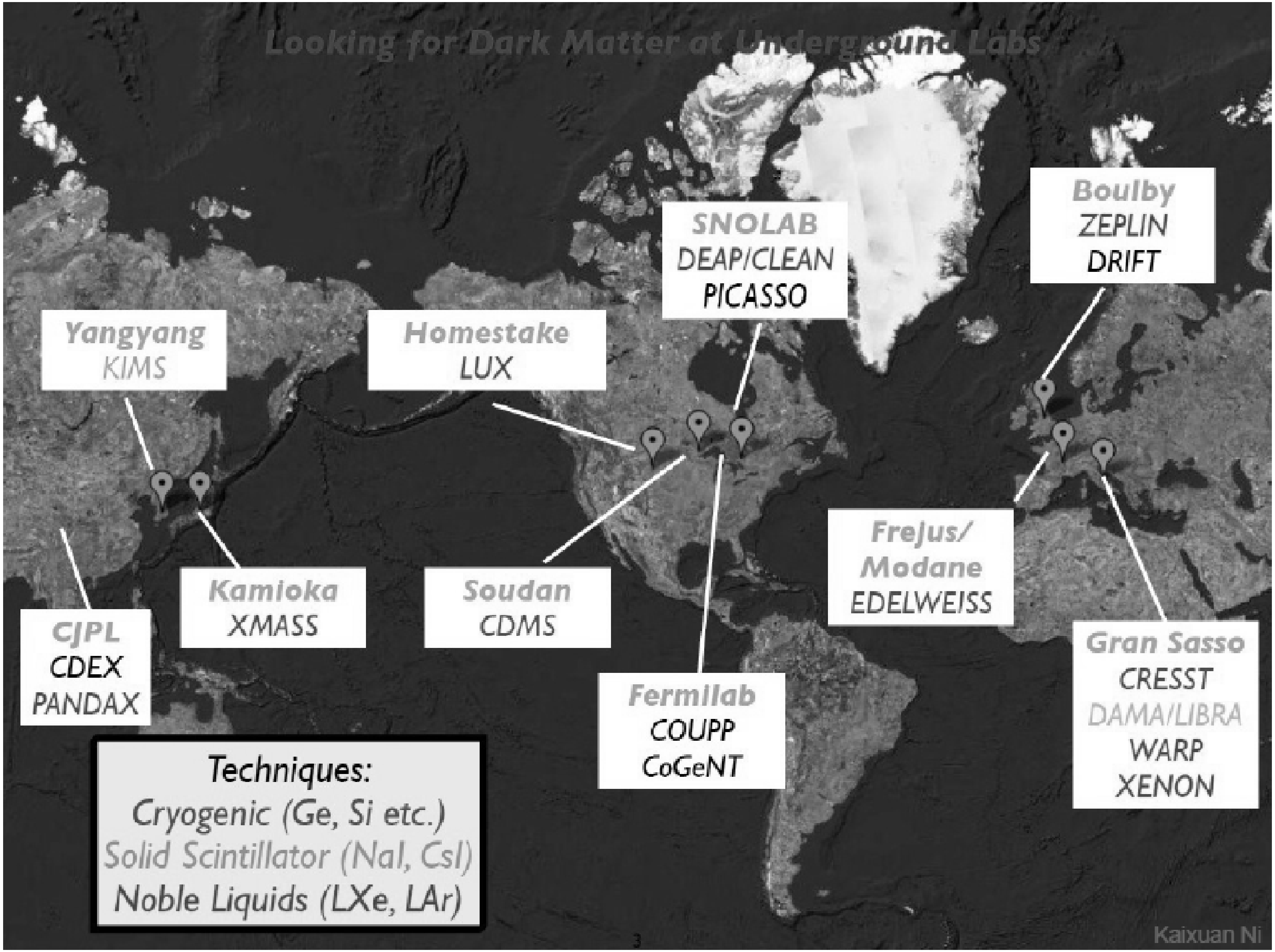
10.3 Background

Ge spectrum unshielded underground

- Despite the detectors being underground, there is still the possibility of background particles being present and interact with the detector.
- Most direct detection experiments do a second independent measurement of the energy deposited by the recoil nucleon, such as total energy and specific ionization. This allows rejection of background.



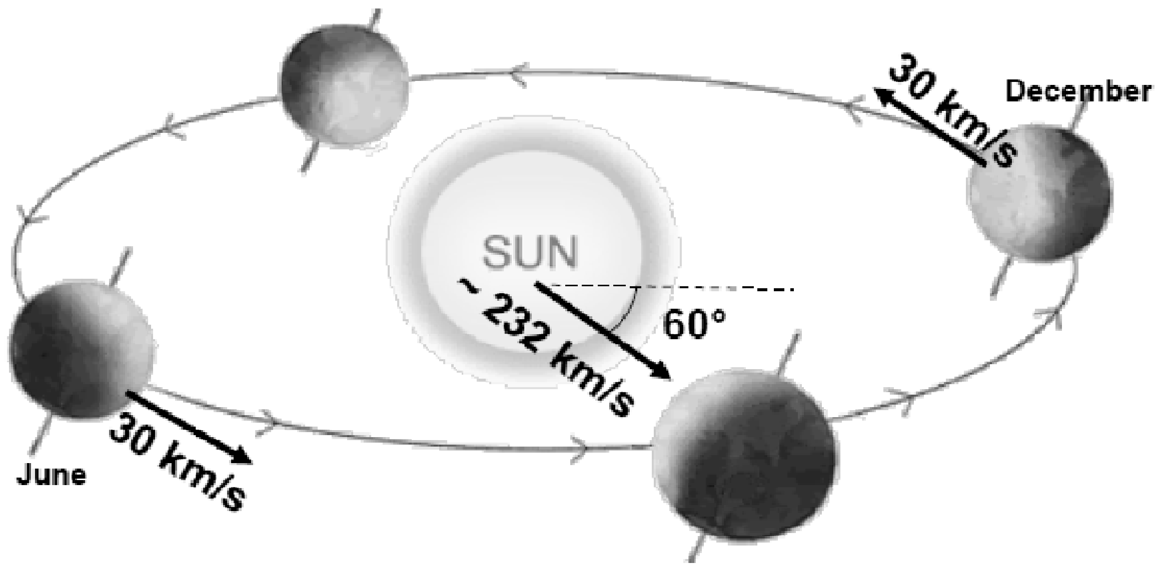
Ge spectrum underground with Pb shield and purge for Rn



Looking for Dark Matter at Underground Labs
Boulby
ZEPLIN
DRIFT
SNOLAB
DEAP/CLEAN
PICASSO
Yangyang
KIMS
Homestake
LUX
Frejus/
Modane
EDELWEISS
Kamioka
XMASS
Soudan
CDMS
CJPL
CDEX
PANDAX
Gran Sasso
CRESST
DAMA/LIBRA
WARP
XENON
Fermilab
COUPP
CoGeNT
Techniques:
Cryogenic (Ge, Si etc.)
Solid Scintillator (NaI, CsI)
Noble Liquids (LXe, LAr)
Kaixuan Ni

10.4 Annual modulation of WIMPs

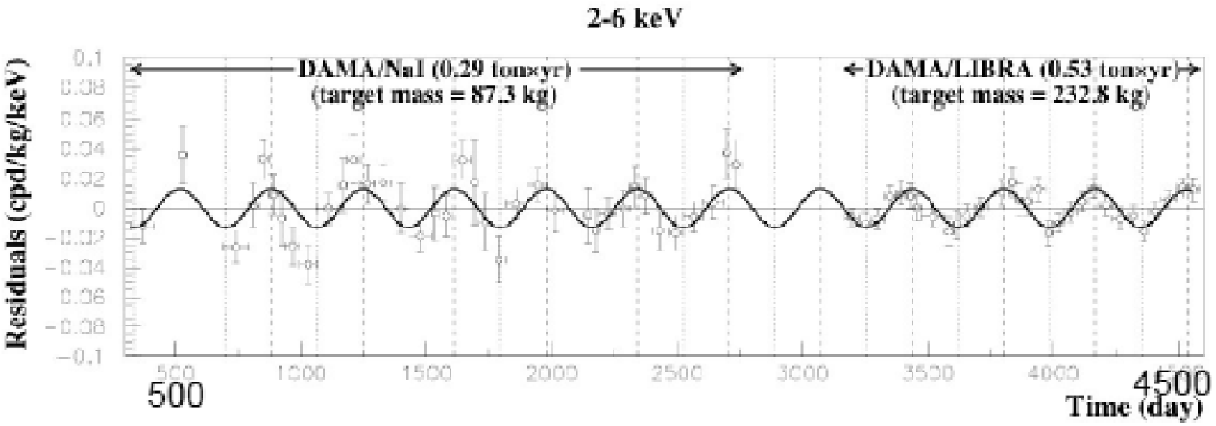
- Different approach: infer the presence of DM from annual modulation
- As the Earth orbits the Sun, it changes its direction in the dark matter halo thus altering the dark matter flux into the detector. This should then lead to an annual modulation in the detected recoils.
- Only one dedicated experiment takes this approach, DAMA, and that have reported an annual modulation

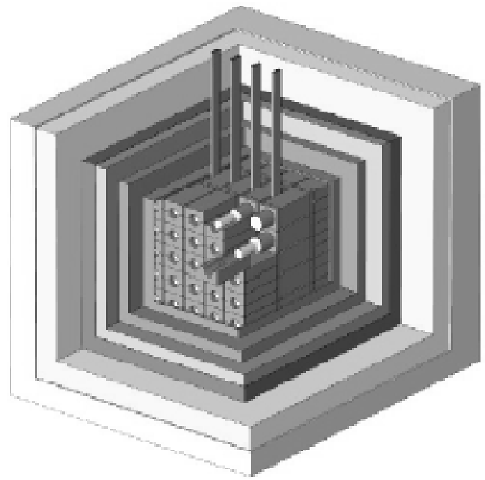


Signals?

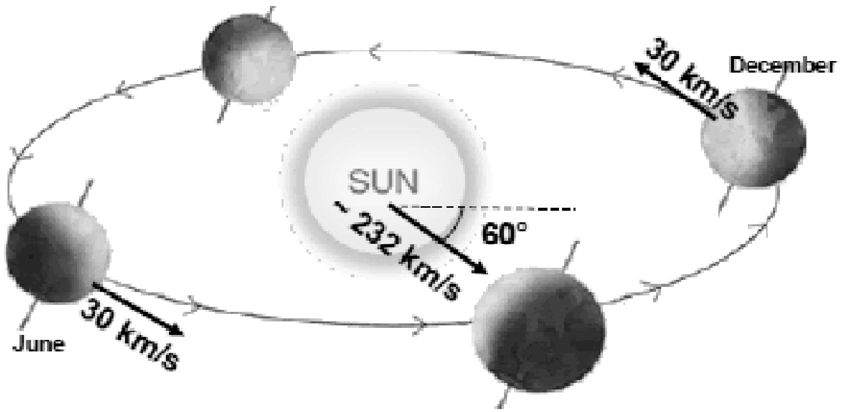
DAMA/LIBRA Annual Modulation

R. Bernabei et al. EPJ C 56, 333 (2008), arxiv:0804.2741
EPJ C 67, 39 (2010), arxiv:1002.1028





- ~250 kg of NaI counters
- 1.17 ton-year exposure (2010)



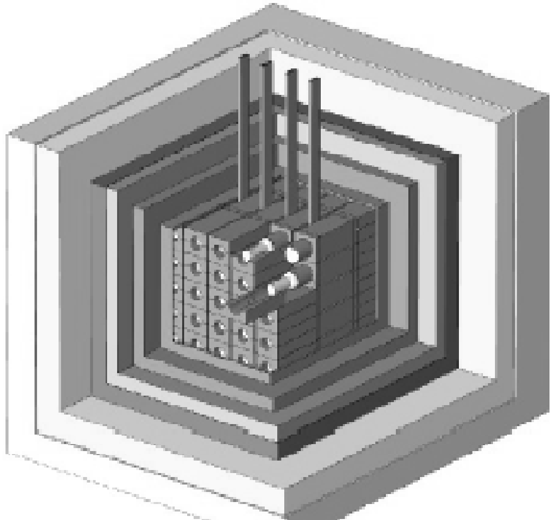
Drukier, Freese, Spergel PRD 86
Freese et al. PRD 88

- Modulation in 2-6 keV single hits: 8.9 σ
- Mostly in 2-4 keV, ~0.02 cts/d/kg/keV
- Total single rate ~1 cts/d/kg/keV
- Standard DM distribution: < ~5% modulation
- Period & phase about right for DM.
- No annual modulation in 6-14 keV.
- No annual modulation in multiple hits. (which?)
- **DM detection?**
- Conflict with other experiments in standard scenarios that test the larger steady state effect.

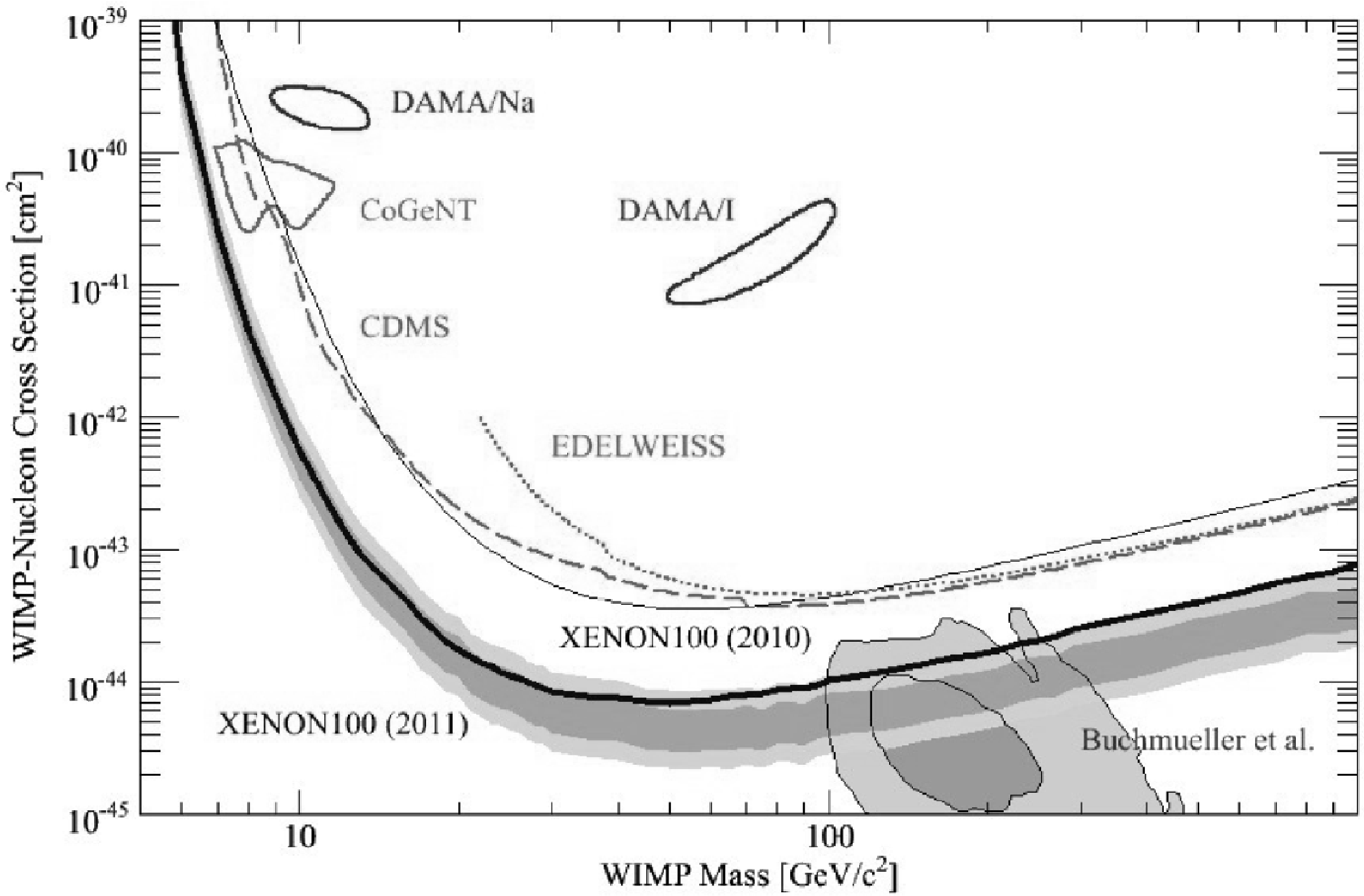
DAMA/LIBRA

R. Bernabei et al. arXiv:0804.2738, arxiv:1002.1028

- Successor of DAMA/NaI experiment
- 5x5 array of 9.7 kg NaI(Tl) crystals viewed by 2 PMTs each.
- PMTs with single photoelectron threshold, operating in coincidence.
- Total mass:
  - DAMA/NaI 1996-2002: ~100 kg
  - DAMA/LIBRA 2003-2008: 232.8 kg
  - DAMA/LIBRA: since 11/2008: 242.5 kg
- Heavy shield:
  >10 cm of Cu, 15 cm of Pb + Cd foils,
  10/40 cm PE/paraffin, ~1 m concrete
- Radon sealing



Exclusion/Signal region



10.5 Xenon experiment@LNGS

Collaboration: US (3)+ Switzerland (1) + Italy (2) + Portugal (1)
+ Germany (3) + France (1) + Netherlands (1) + Israel (1) + China (1)

GOAL: Explore WIMP Dark Matter with a sensitivity of $\sigma_{SI}\sim10^{-47}$ cm^2.

- Requires ton-scale fiducial volume with extremely low background.

CONCEPT:

- Target LXe: excellent for DM WIMPs scattering.
  - Sensitive to both axial and scalar coupling.
- Detector: two-phase XeTPC: 3D position sensitive, self-shielding.
- Background discrimination: simultaneous charge & light detection (>99.5%).
- PMT readout with >3 pe/keV. Low energy threshold for nuclear recoils (~5 keV).

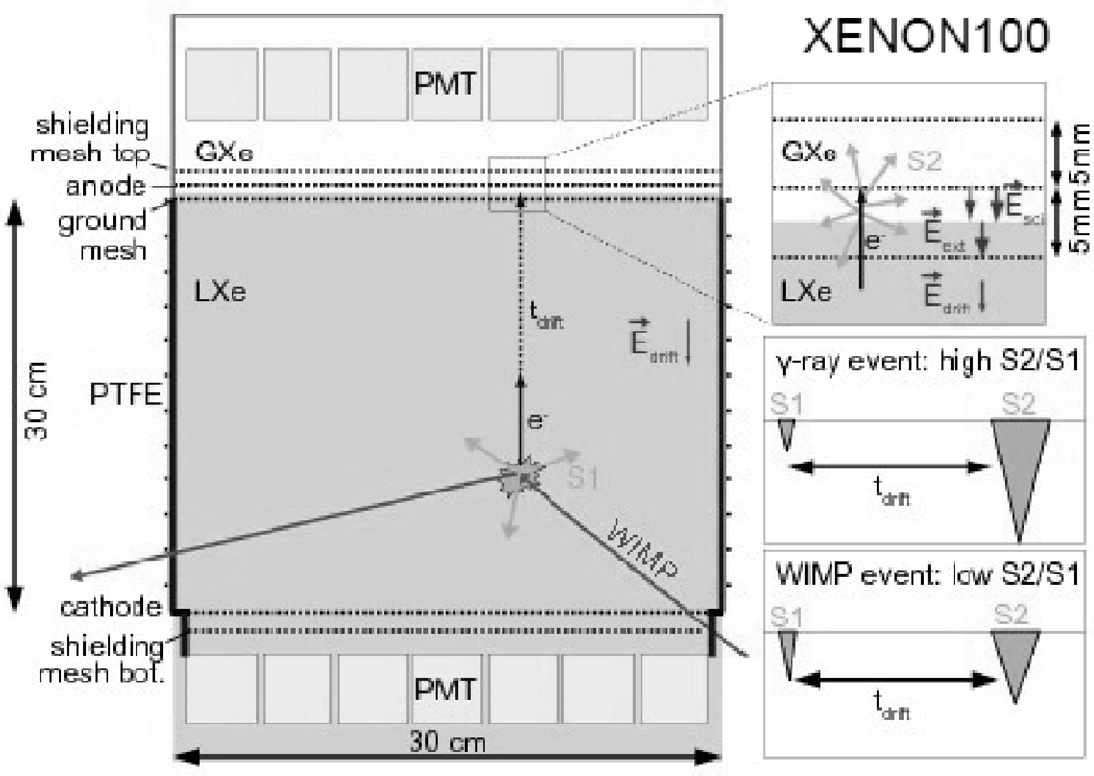
PHASES:

R&D	XENON10	XENON100	XENON1T
Start: 2002	2005-2007	2008-2011+	2011-2015
	Proof of concept. Total mass: 14 kg 15 cm drift. Best limit in '07: $\sigma_{SI}\sim10^{-43}$ cm^2	Dark Matter run ongoing. Total mass: 170 kg 30 cm drift. 2011: $\sigma_{SI}\sim 7 \times 10^{-45}$ cm^2 Goal: $\sigma_{SI}\sim 2 \times 10^{-45}$ cm^2	Technical design studies. Total mass: ~2.5 t 90 cm drift. Goal: $\sigma_{SI} \sim 3 \times 10^{-47}$ cm^2

The Liquid Xenon Dual Phase TPC

Ionization + Scintillation

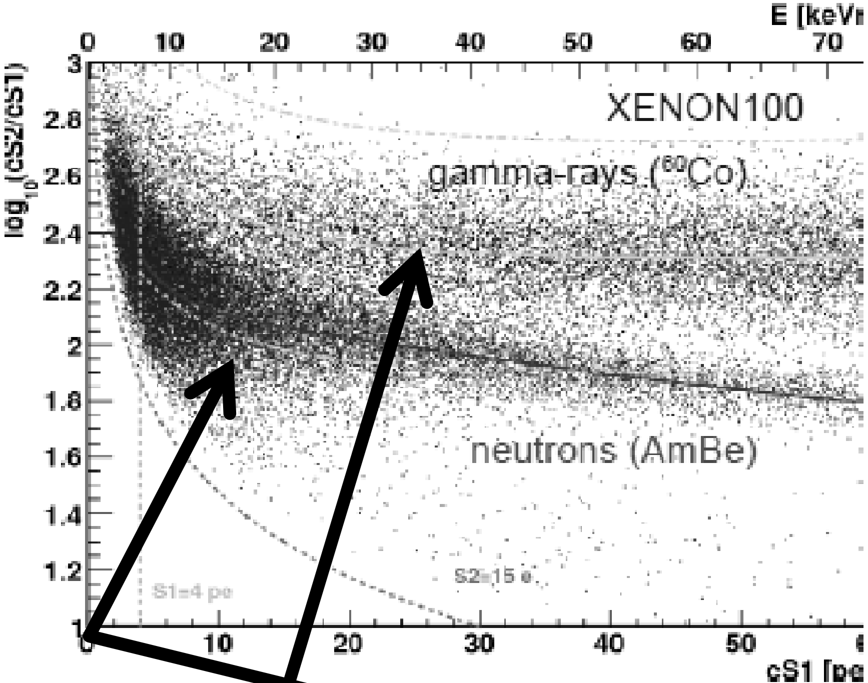
- Wimp recoil on Xe nucleus in dense liquid (2.9 g/cm^3) → Ionization + UV Scintillation
- Detection of primary scintillation light (S1) with PMTs.
- Charge drift towards liquid/gas interface.
- Charge extraction liquid/gas at high field between ground mesh (liquid) and anode (gas)
- Charge produces proportional scintillation signal (S2) in the gas phase (10 kV/cm)



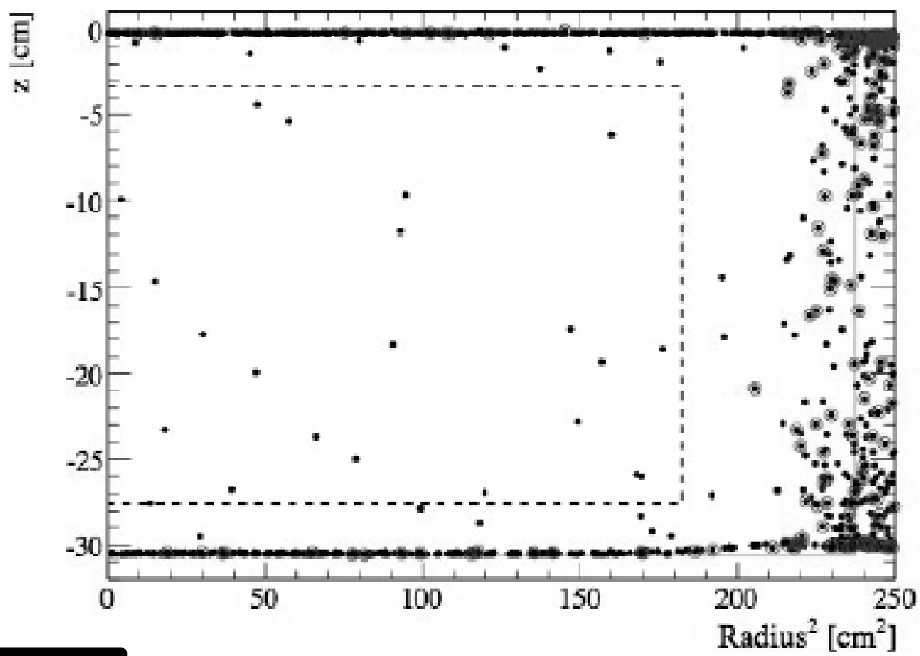
- 3D position measurement:
  - X/Y from S2 signal. Resolution few mm.
  - Z from electron drift time (~1 mm).

Background Discrimination in Dual Phase Liquid Xenon TPC's

Ionization/Scintillation Ratio S2/S1



3D Position Resolution: fiducial cut, singles/multiples



Signal simulation

background

Summary for Direct Searches

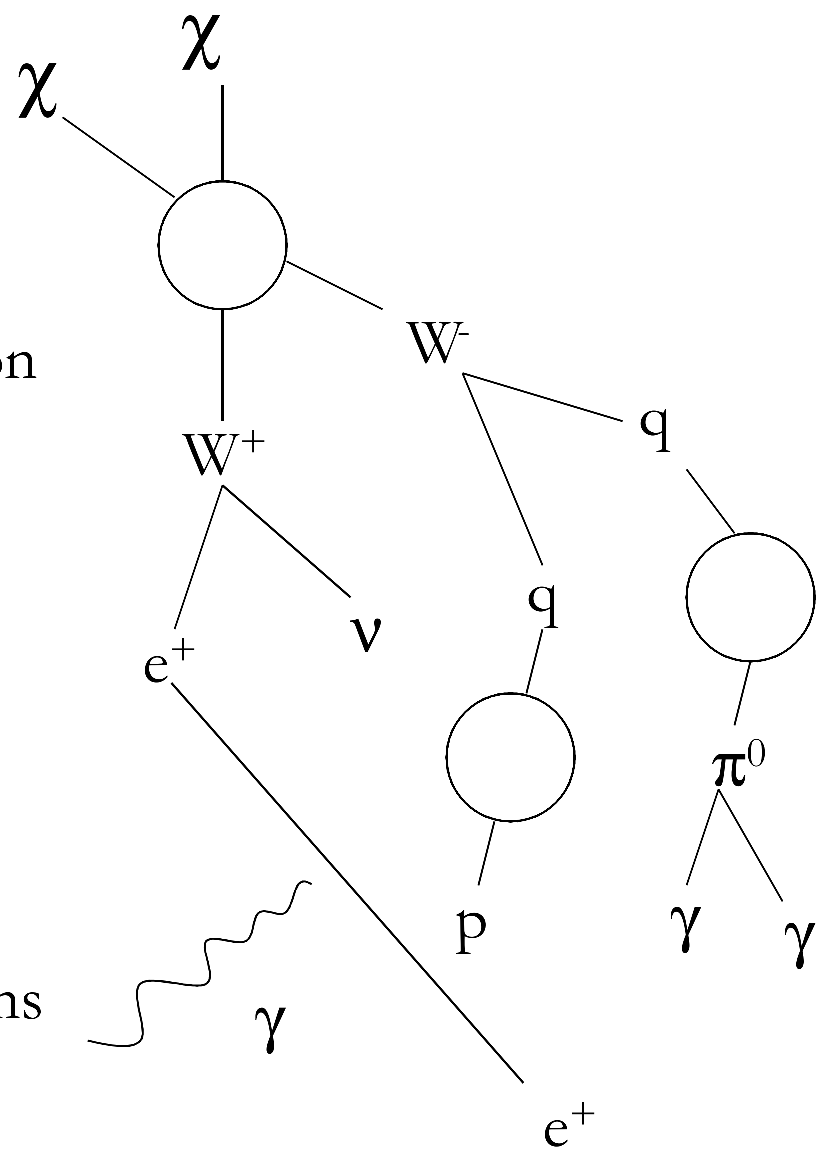
- **Progress in Dark Matter direct searches:**
  - Sensitivity advanced by ~3 orders of magnitude in the last decade, increasing pace.
  - Noble liquid detectors are starting to set the pace in sensitivity.
- **Exciting new results in the last year**:
  - CoGeNT, CRESST excess events & DAMA/LIBRA annual modulation:
    Low mass WIMPs with $\sigma_S \sim 10^{-40}$ cm^2 @ ~7 GeV/c^2? Or poorly understood backgrounds?
    CoGeNT new result June 2011: annual modulation?
- **New XENON100 result April 2011**:
  - Upper limit on (spin-independent) WIMP-nucleon cross-section
    $\sigma_s = 7.0\times10^{-45}$ cm^2 @ 50 GeV/c^2
    ~ Factor 5 improvement over previous limits.
  - XENON100 challenges the low mass WIMP interpretation. (+ low threshold CDMS)
  - Inelastic DM (nearly) ruled out as explanation for annual modulation in DAMA/LIBRA.
- **The future looks exciting:**
  - Rapid progress at the LHC:
    Limits on new physics improving fast. Will we see SUSY soon?
  - New results in indirect searches:
    but fundamental problems of background subtraction remain (so far).
  - Direct + indirect searches + LHC:
    We will know much more about DM within the next 5 years.
    If DM consists of WIMPs we will likely have found signs of them.

10.6 The Indirect Detection of DM

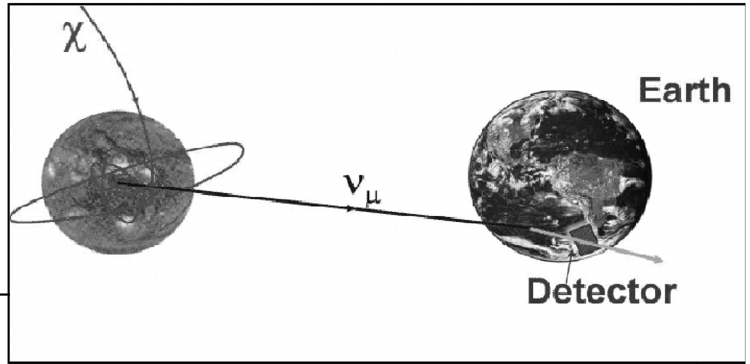
❑ **WIMP Annihilation**
Typical final states include heavy fermions, gauge or Higgs bosons

❑**Fragmentation/Decay** Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, neutrinos and gamma-rays

❑**Synchrotron and Inverse Compton** Relativistic electrons up-scatter starlight/CMB to MeV-GeV energies, and emit synchrotron photons via interactions with magnetic fields



The Indirect Detection of DM

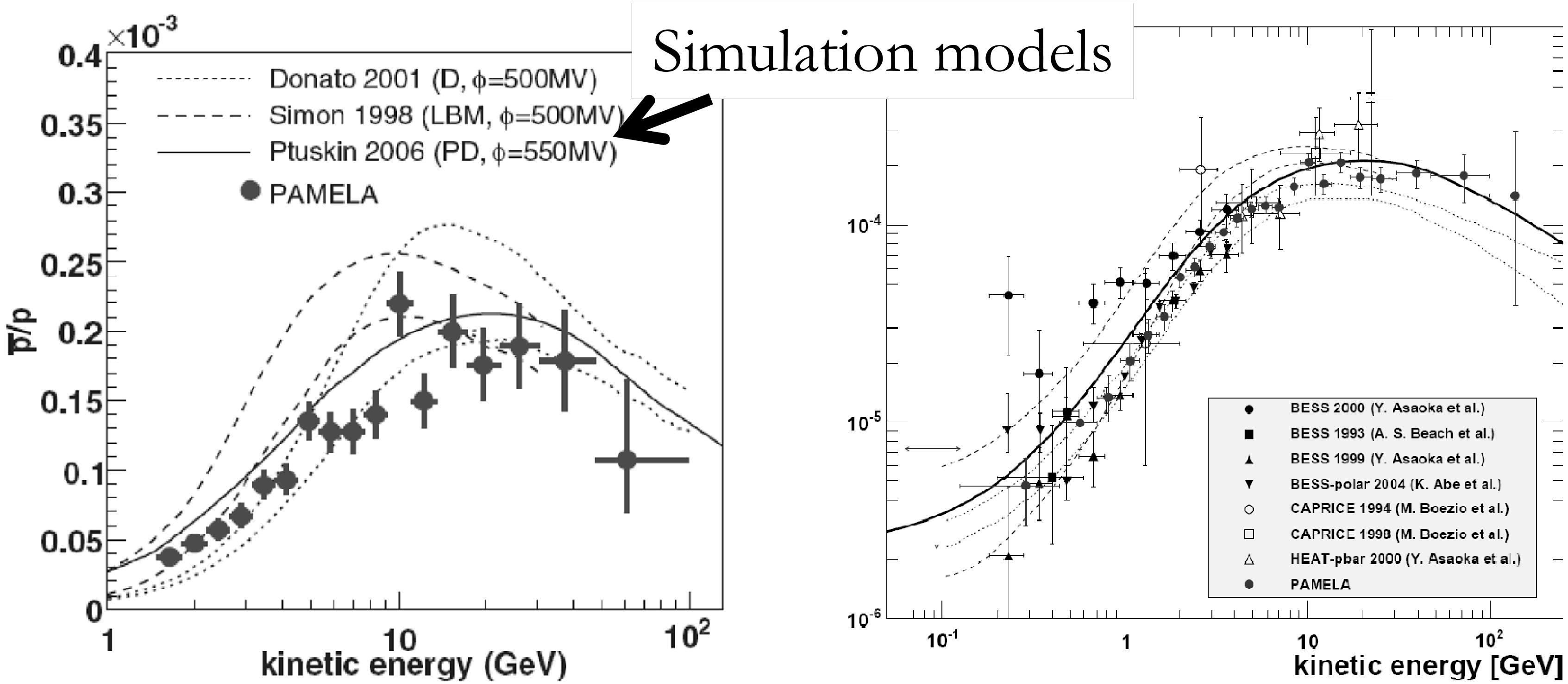


- **Neutrinos** from annihilations in the core of the Sun (ANTARES, IceCube)
- **Gamma Rays** from annihilations in the galactic halo, near the galactic center, in dwarf galaxies, etc.

- **Positrons/Antiprotons** from annihilations throughout the galactic halo

- Measured in space–based detectors: Fermi (gammas), PAMELA, AMS (antimatter) or in atmospheric telescopes: MAGIC, HESS, VERITAS, CANGAROO (gammas)

Antimatter measured by PAMELA - $\bar{p}$



- PAMELA results are consistent with pure secondary production of **antiprotons** during the propagation of cosmic rays in the galaxy

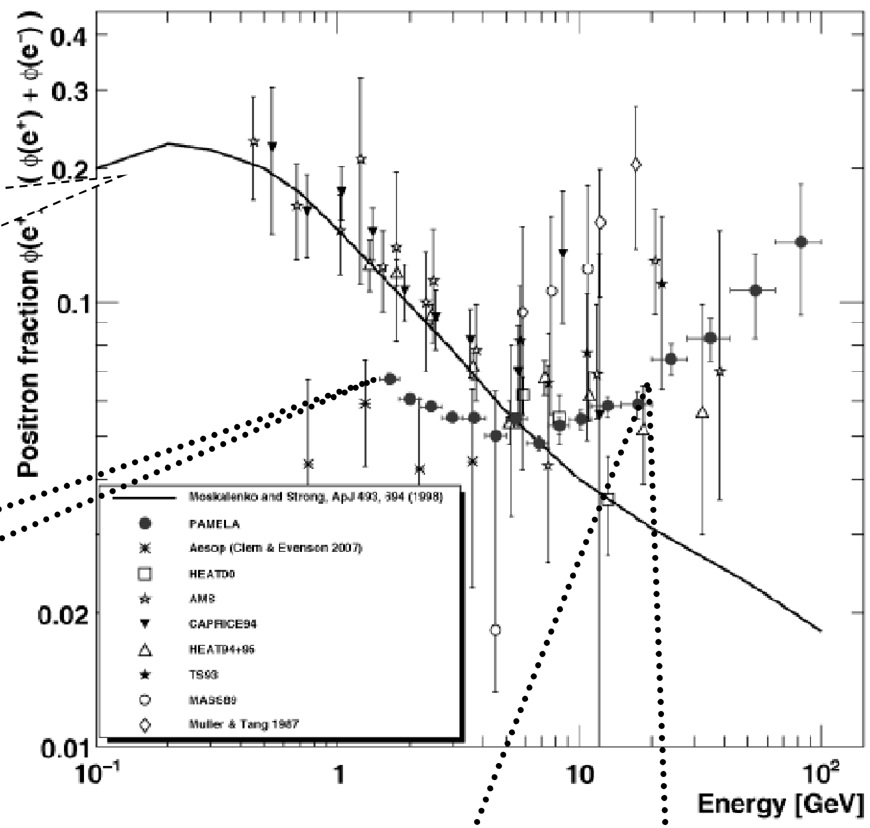
PAMELA: Positron fraction

■(Moskalenko & Strong 1998)

■GALPROP code

• Plain diffusion model

• Interstellar spectra



■Solar modulation effects

■**Rapid climb above 10 GeV indicates the presence of a <u>primary source of cosmic ray positrons</u>**

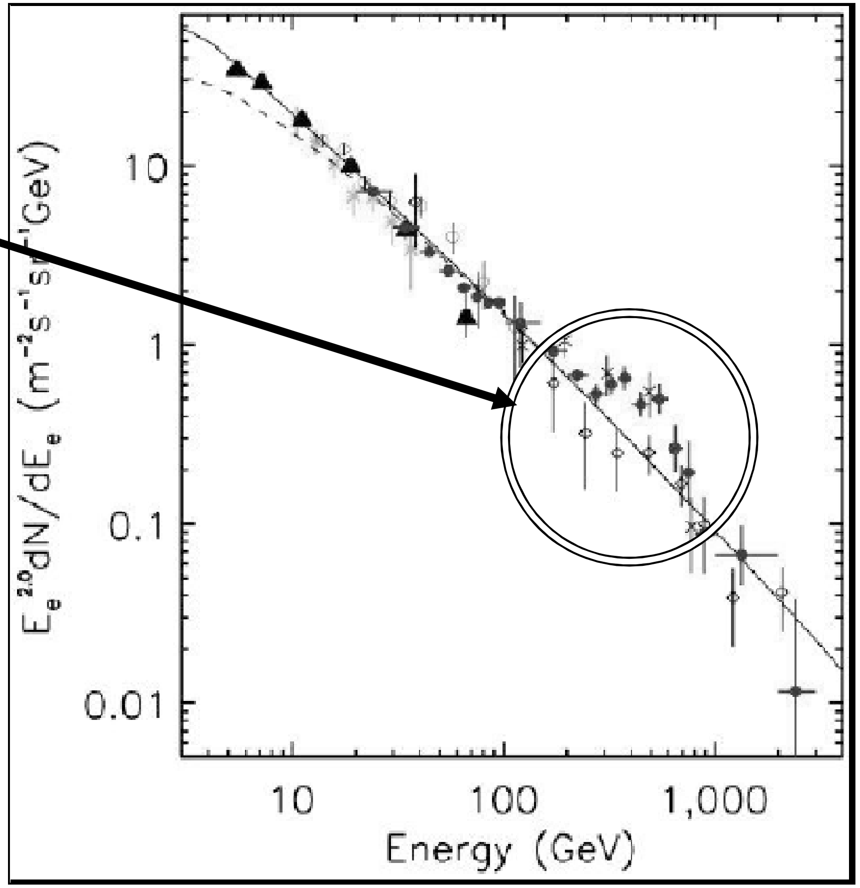
- Explanations*:
  - Dark matter;
  - **Astrophysical processes**
  - **??**

The New Cosmic Ray Electron Spectrum From ATIC balloon

- In a series of balloon flights, ATIC has measured an excess of cosmic ray electrons between 300 and 800 GeV (Nature, Nov. 21, 2008)

- This requires a ***local*** source of cosmic ray electrons/positrons (within ~1 kpc)

- If we extrapolate the Pamela positron fraction up to higher energies, the ATIC result approximately matches

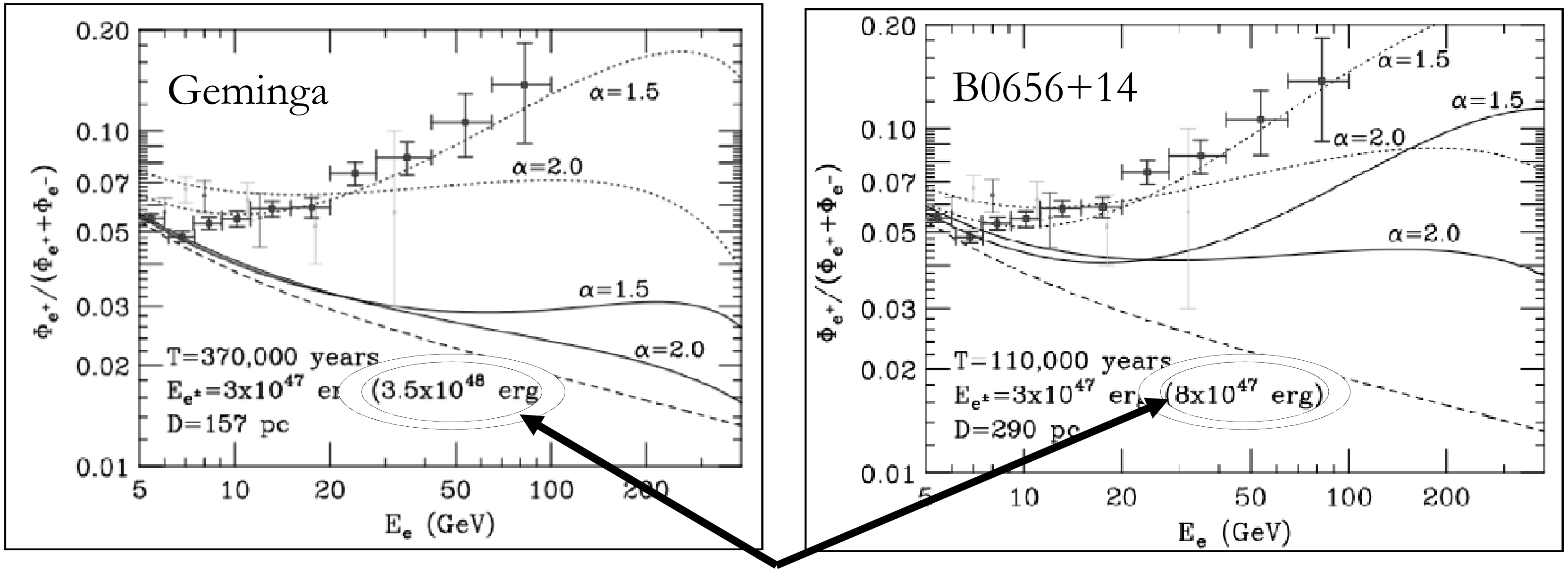


HE Positrons from a nearby Pulsars?

- Rapidly spinning (~msec) neutron stars, accelerate electrons to VH energies
- Energies can exceed the pair production threshold
- Very young pulsars (<10,000 years) are typically surrounded by a pulsar wind nebula, which can absorb energetic pairs

Two promising candidates:

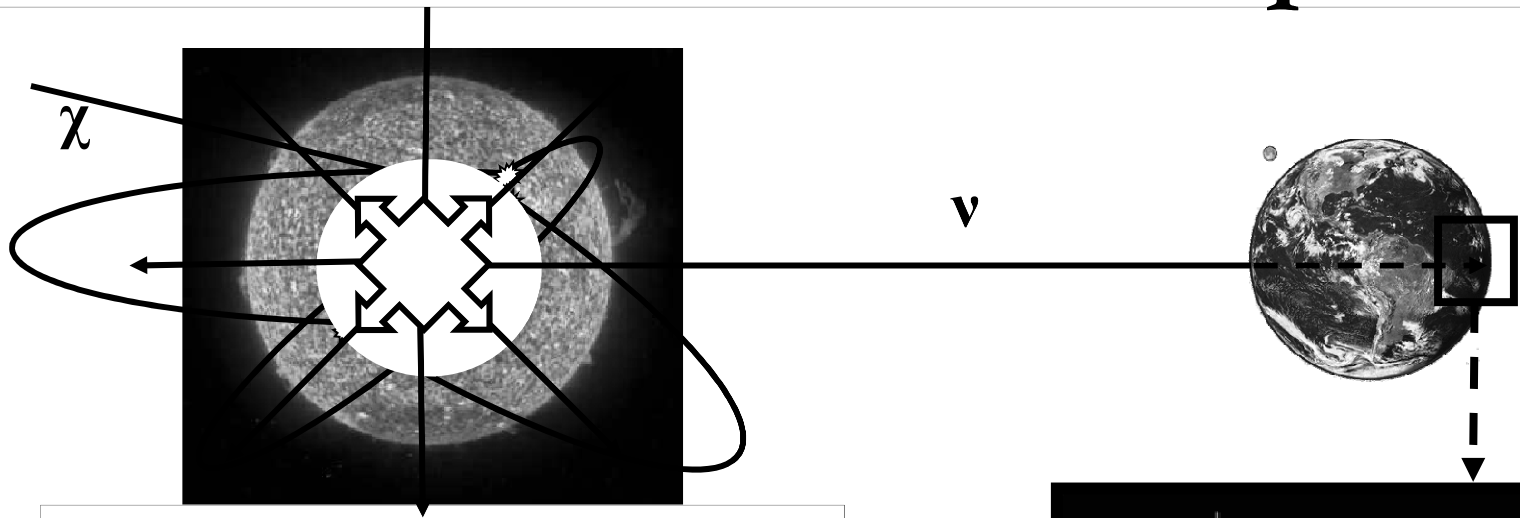
- **Geminga** (157 pc away, 370,000 years old)
- **B0656+14** (290 pc, 110,000 years)



A few percent of the total spindown energy is needed in high energy e^+e^- pairs

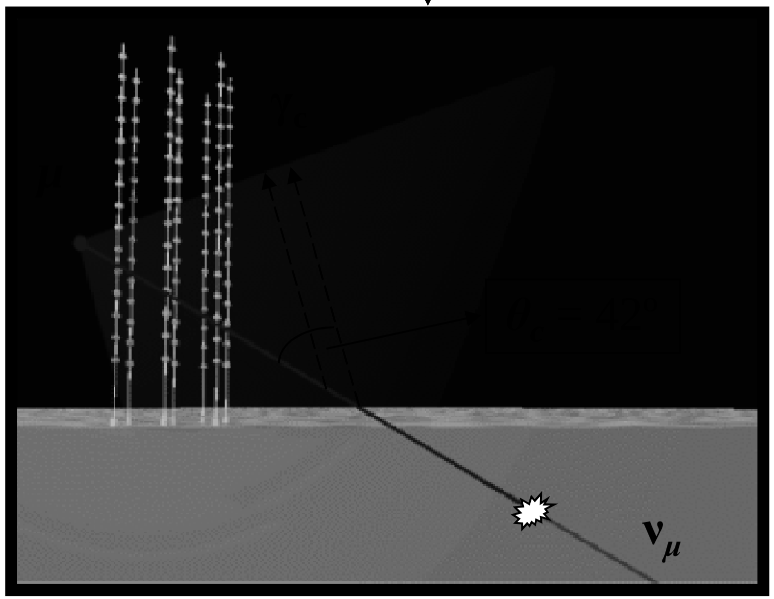
Hooper, P. Blasi, P. Serpico, JCAP, arXiv:0810.1527

Dark Matter detection with a neutrino telescope



Detection principle:

- ***Dark matter consists of relic WIMPs created in the early Universe***



Conclusions

- There are impressive experimental efforts by many groups around the world to detect the dark matter: DAMA, CoGeNT, CRESST, CDMS, XENON,…, Fermi, PAMELA, etc.
- The present experimental situation is very exciting.
- And, besides, the LHC is working
- Stay tuned !


THE END
DM
detection
project
experiments
also
groups
MAGIC
mass
group
searches
energy
candidates
collaboration
FERMI
Spanish
analysis
different
data
new
indirect
direct
MULTIDARK
neutralino
important
existing
ANTARES
structure
halo
results
search
dark
years
physics
signal
large
space
particle
Universe
provide
number
de
ANAIS
study
formation
decay
GeV
like
flux
case
promote
observations
good
interesting
sensitivity
detected
proposed
made
Matter
already
CTA
neutrinos
particles
light
analyses
particular
present
Physics
detectors
see
Fig
work
way
candidate
example
account
obtained
use
carried
high
now
e.g
IFAE
targets
DDM
AUGER
context
SUSY
distribution
Spain
annihilation
future
telescopes
matter
first
members
LSP
detector
field
European
Milestone
support
experimental
WIMPs
Although
model
halos
using
interaction
KM3NeT
keV
still
well
order
theoretical
Dark
WIMP
Astroparticle
design
models
proposal
crucial
expected
density
around
may
due
galactic
neutrino
experiment
possible
UAM/IFT
range
parameter
gravitino
SHDM
role
etc
working
telescope
masses
scientific
might
gamma-ray
research
studies
produced
standard
simulations
sources
one