Dark Matter: experimental techniques/ issues

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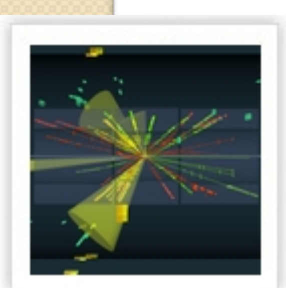
MultiDark
Multimessenger Approach for Dark Matter Detection

Universidad Zaragoza
1542



Taller de Altas Energías 2015
2015, 28-29th September
Benasque, HUESCA

LSC
Laboratorio Subterráneo de Canfranc

The Dark Matter Problem

Understanding of the Universe at galactic and cosmological scales requires

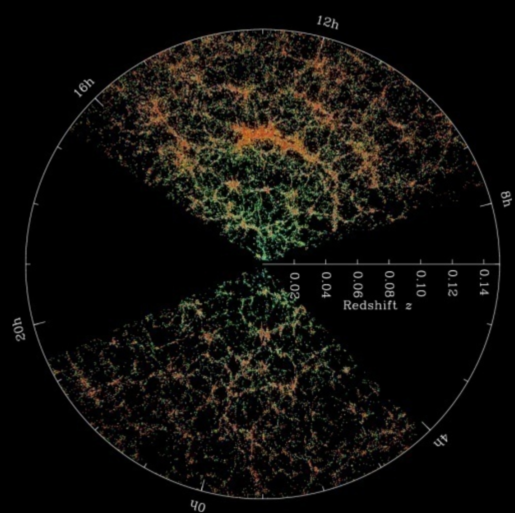
DARK MATTER

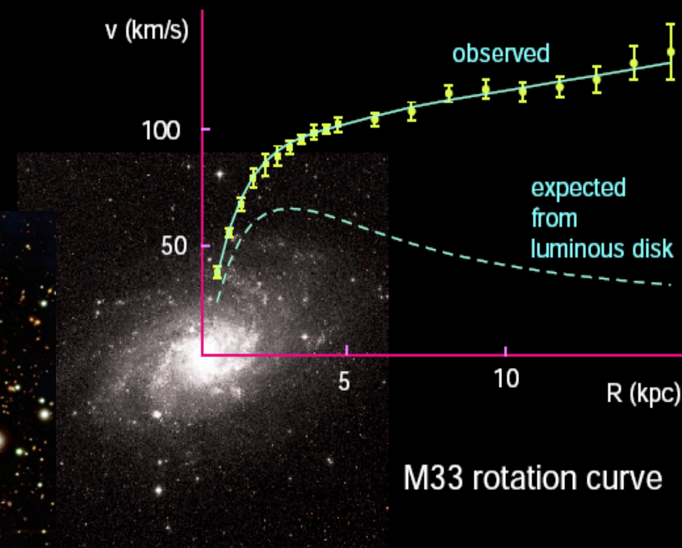
+

DARK ENERGY

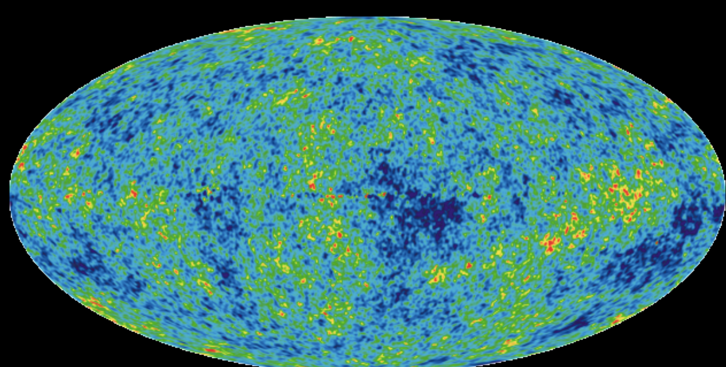
The Dark Matter Problem

Evidences come from very different observational techniques at different scales and times of the Universe history

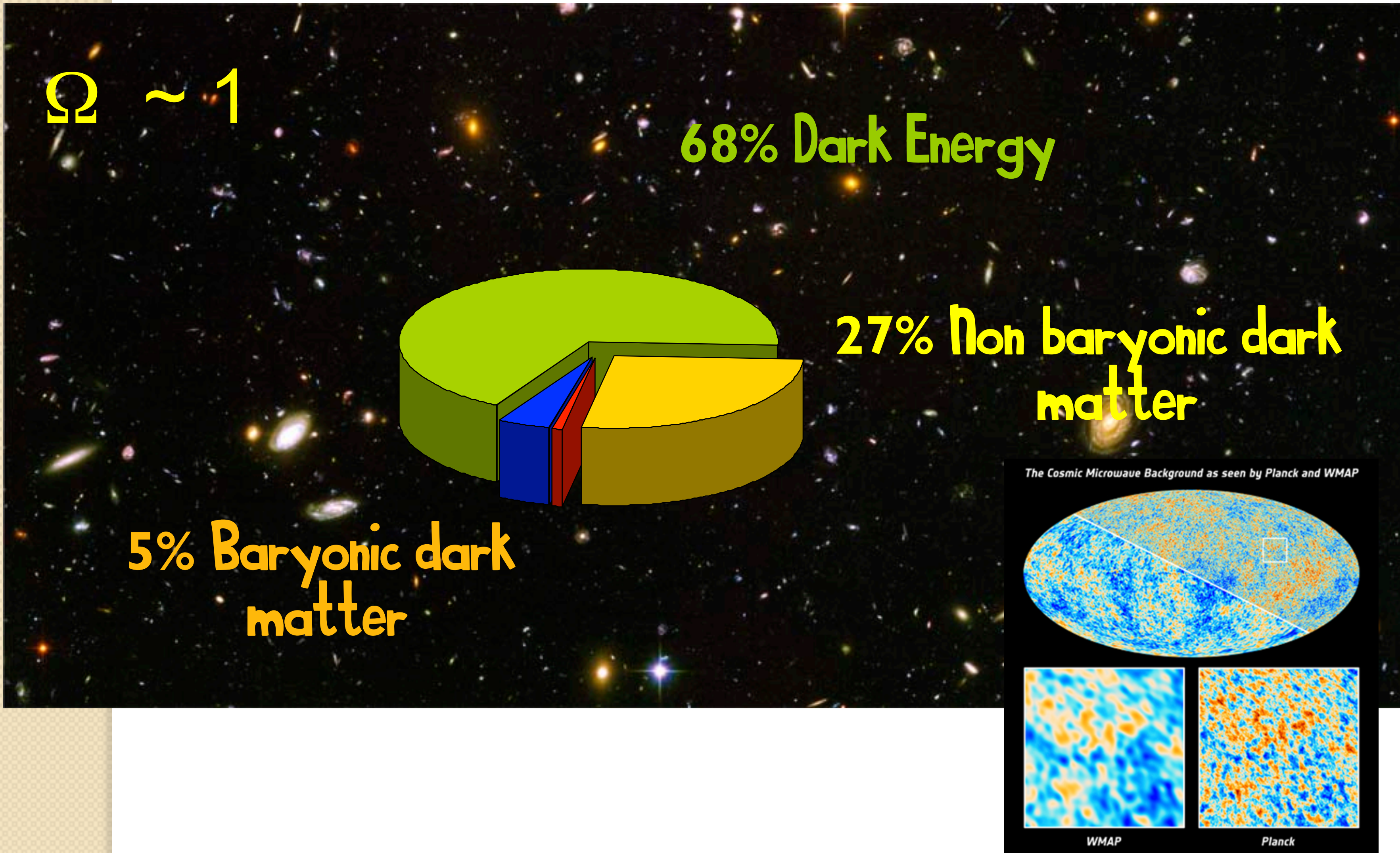




M33 rotation curve

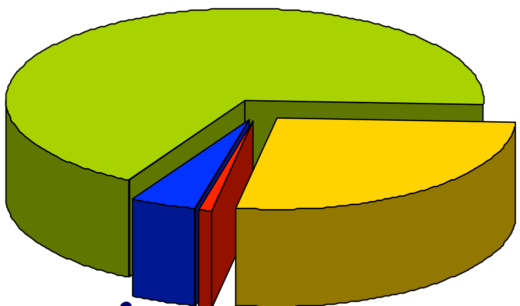


The Universe Recipe… after PLANCK



The Universe Recipe… after PLANCK

68% Dark Energy



5% Baryonic Dark Matter

27% Non Baryonic Dark Matter

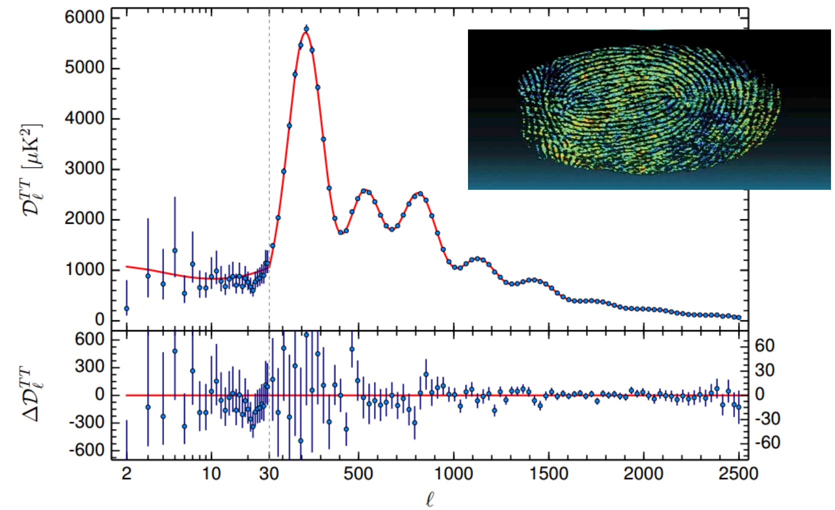


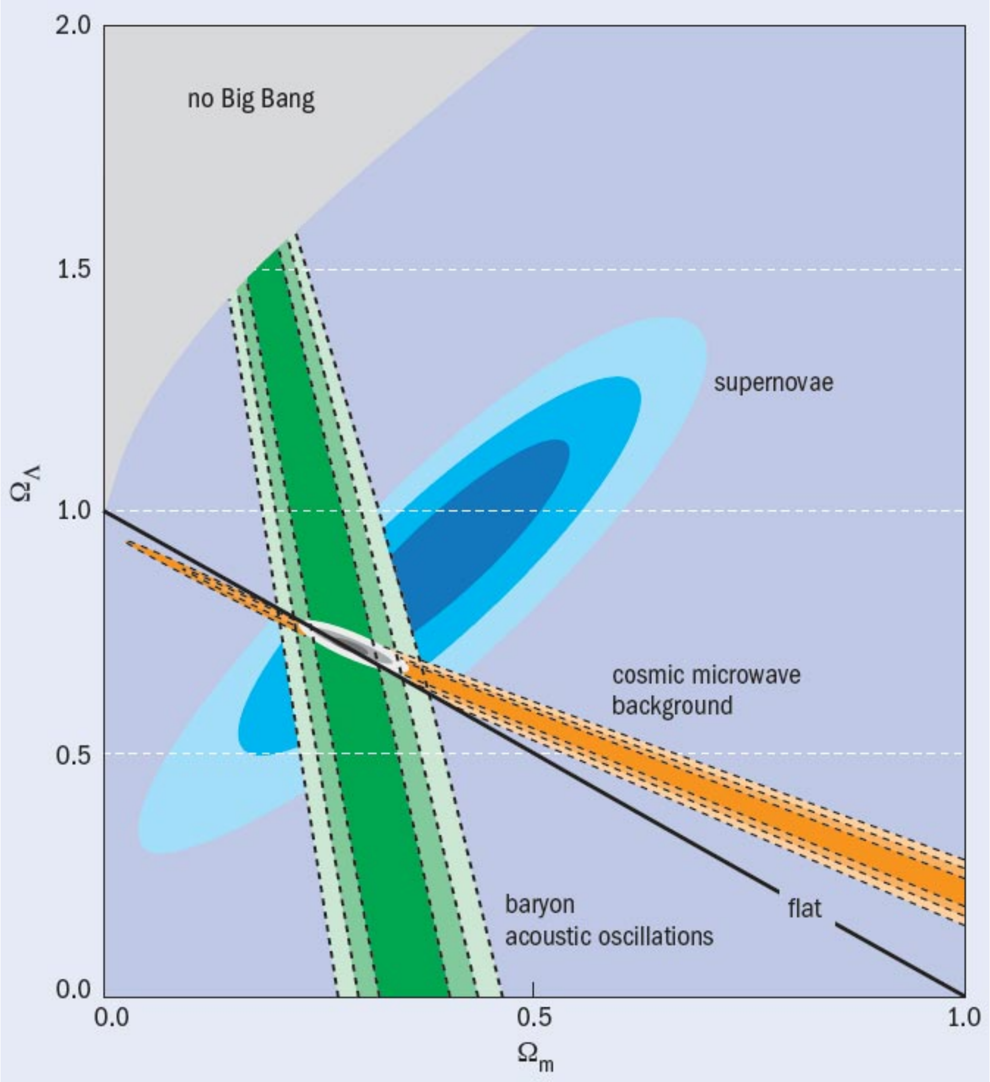
Table 4. Parameter 68 % confidence limits for the base ΛCDM model from *Planck* CMB power spectra, in combination with lensing reconstruction ("lensing") and external data ("ext," BAO+JLA+H_0). Nuisance parameters are not listed for brevity (they can be found in the *Planck Legacy Archive* tables), but the last three parameters give a summary measure of the total foreground amplitude (in μK^2) at $\ell = 2000$ for the three high-ℓ temperature spectra used by the likelihood. In all cases the helium mass fraction used is predicted by BBN (posterior mean $Y_P \approx 0.2453$, with theoretical uncertainties in the BBN predictions dominating over the *Planck* error on $\Omega_b h^2$).

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062
$\Omega_m h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	0.1413 ± 0.0011	0.1427 ± 0.0014	0.1422 ± 0.0013	0.14170 ± 0.00097
$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029	0.09596 ± 0.00030	0.09598 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086
$\sigma_8 \Omega_m^{0.5}$	0.466 ± 0.013	0.4521 ± 0.0088	0.4514 ± 0.0066	0.4668 ± 0.0098	0.4553 ± 0.0068	0.4535 ± 0.0059
$\sigma_8 \Omega_m^{0.25}$	0.621 ± 0.013	0.6069 ± 0.0076	0.6066 ± 0.0070	0.623 ± 0.011	0.6091 ± 0.0067	0.6083 ± 0.0066
z_{re}	$9.9^{+1.8}_{-1.6}$	$8.8^{+1.7}_{-1.4}$	$8.9^{+1.3}_{-1.2}$	$10.0^{+1.7}_{-1.5}$	$8.5^{+1.4}_{-1.2}$	$8.8^{+1.2}_{-1.1}$
$10^9 A_s$	$2.198^{+0.076}_{-0.085}$	2.139 ± 0.063	2.143 ± 0.051	2.207 ± 0.074	2.130 ± 0.053	2.142 ± 0.049
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.874 ± 0.013	1.873 ± 0.011	1.882 ± 0.012	1.878 ± 0.011	1.876 ± 0.011
Age/Gyr	13.813 ± 0.038	13.799 ± 0.038	13.796 ± 0.029	13.813 ± 0.026	13.807 ± 0.026	13.799 ± 0.021
z_*	1090.09 ± 0.42	1089.94 ± 0.42	1089.90 ± 0.30	1090.06 ± 0.30	1090.00 ± 0.29	1089.90 ± 0.23
r_*	144.61 ± 0.49	144.89 ± 0.44	144.93 ± 0.30	144.57 ± 0.32	144.71 ± 0.31	144.81 ± 0.24
$100\theta_*$	1.04105 ± 0.00046	1.04122 ± 0.00045	1.04126 ± 0.00041	1.04096 ± 0.00032	1.04106 ± 0.00031	1.04112 ± 0.00029
z_{drag}	1059.57 ± 0.46	1059.57 ± 0.47	1059.60 ± 0.44	1059.65 ± 0.31	1059.62 ± 0.31	1059.68 ± 0.29
r_{drag}	147.33 ± 0.49	147.60 ± 0.43	147.63 ± 0.32	147.27 ± 0.31	147.41 ± 0.30	147.50 ± 0.24
k_D	0.14050 ± 0.00052	0.14024 ± 0.00047	0.14022 ± 0.00042	0.14059 ± 0.00032	0.14044 ± 0.00032	0.14038 ± 0.00029
z_{eq}	3393 ± 49	3365 ± 44	3361 ± 27	3395 ± 33	3382 ± 32	3371 ± 23
k_{eq}	0.01035 ± 0.00015	0.01027 ± 0.00014	0.010258 ± 0.000083	0.01036 ± 0.00010	0.010322 ± 0.000096	0.010288 ± 0.000071

Interpreted in the cosmological standard model ΛCDM

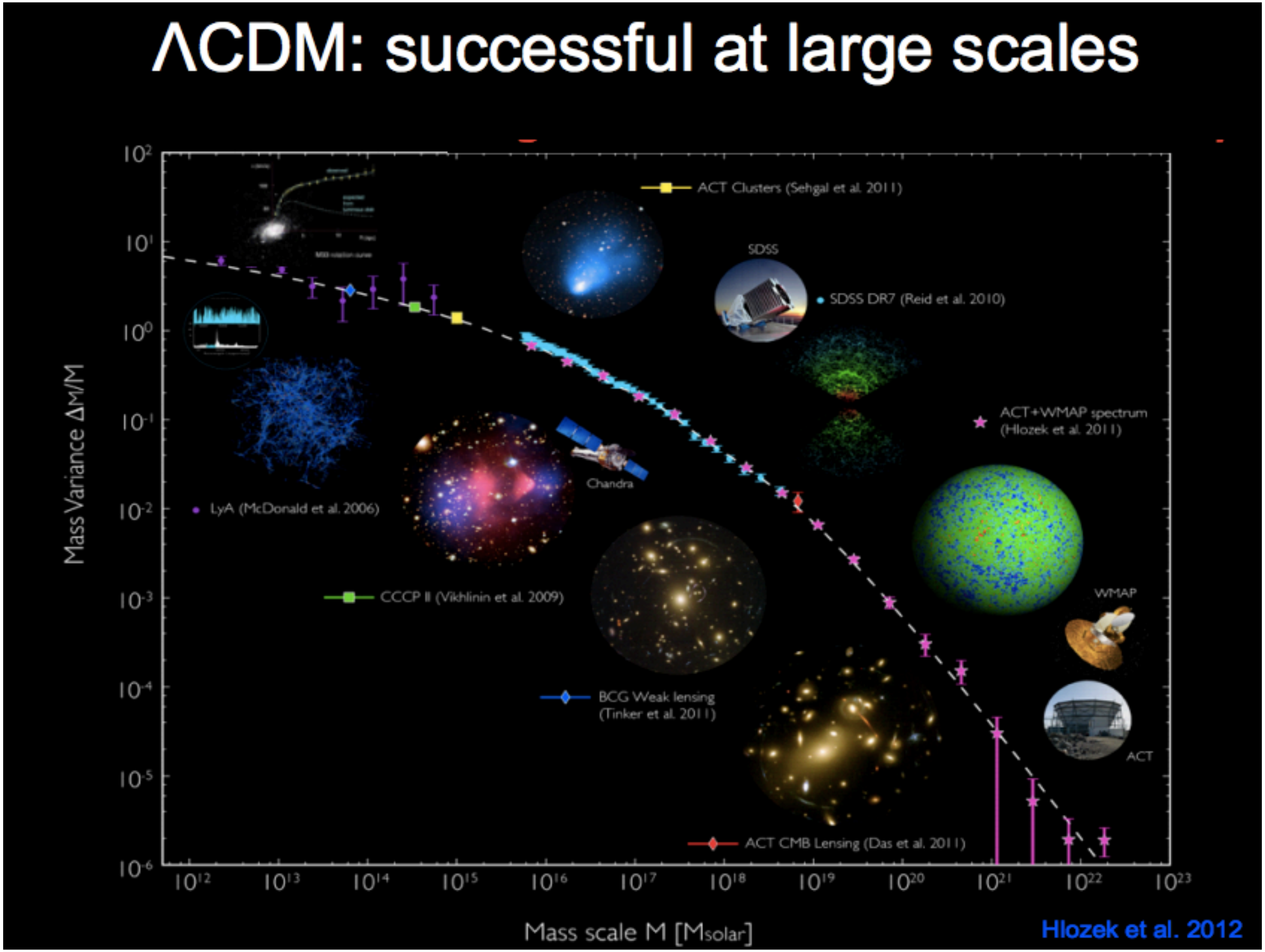
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
Ω_Λ	0.685 ± 0.013
Ω_m	0.315 ± 0.013

A very successful Universe model ΛCDM



Experimental evidences converge in the frame of the standard cosmological model

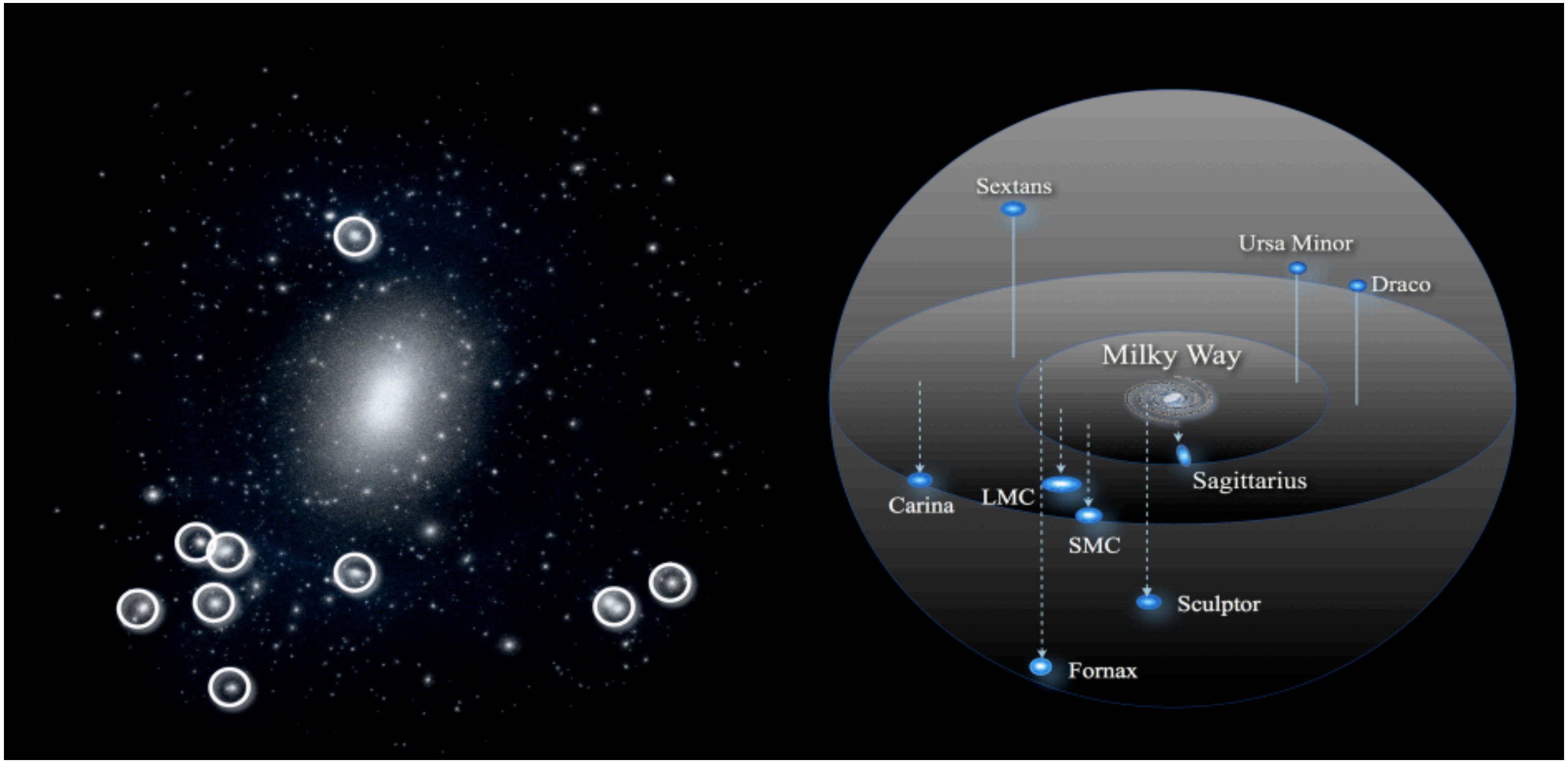
A very successful Universe model ΛCDM



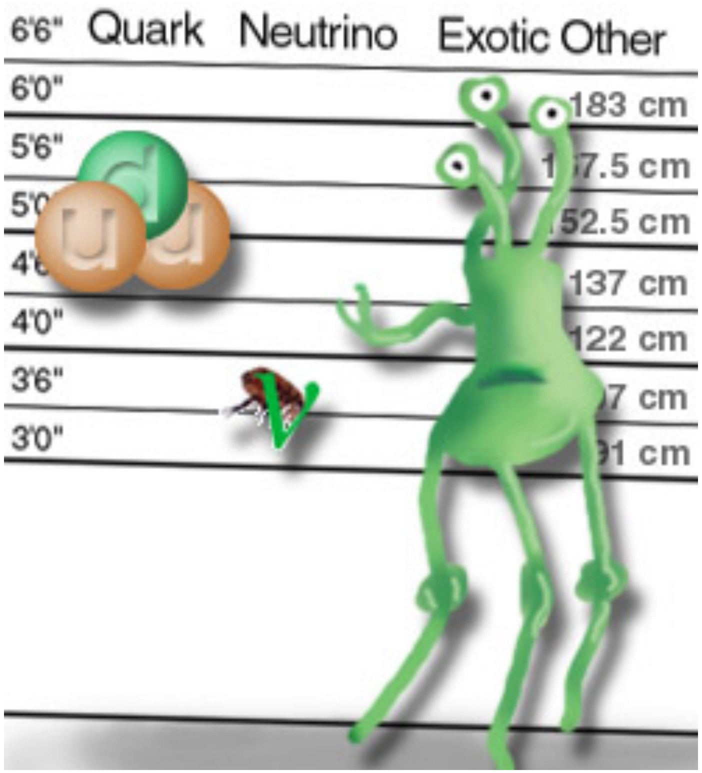
A very successful Universe model ΛCDM

Not so succesful in the small scales

Missing satellites problem
Size of small scale structures



The Dark Matter Nature



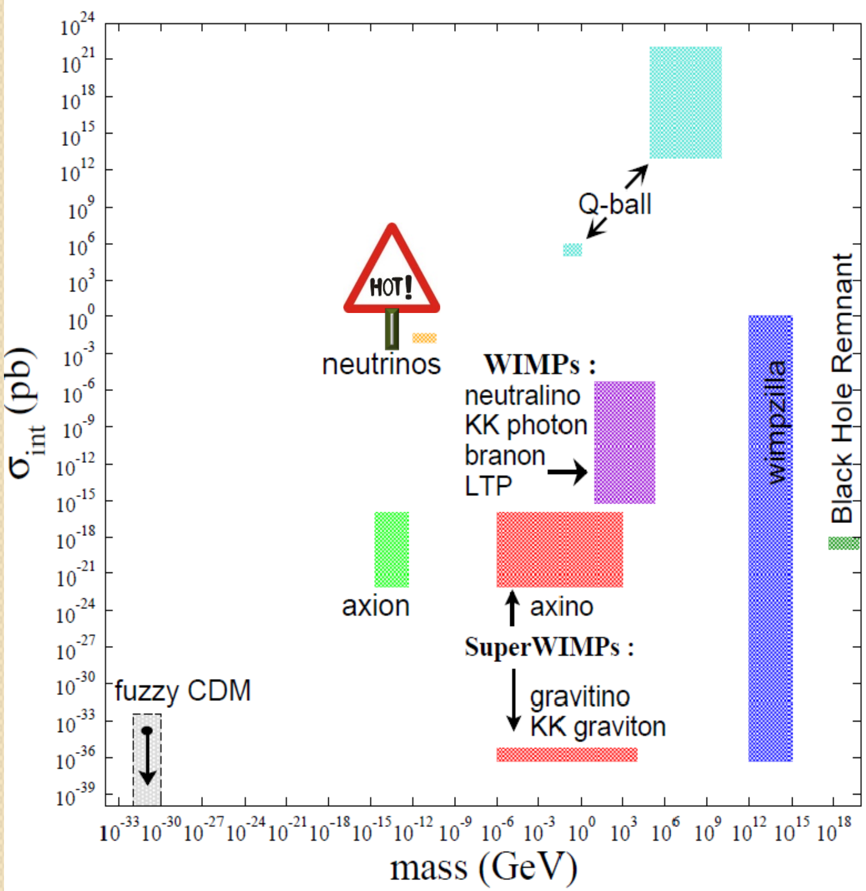
27% of the Universe consists of
UNKNOWN MATTER

- massive
- non baryonic
- neutral
- stable or very long lived
- non relativistic when structures formed (cold/warm)

Beyond the Standard Model of Particle Physics

Dark Matter Candidates

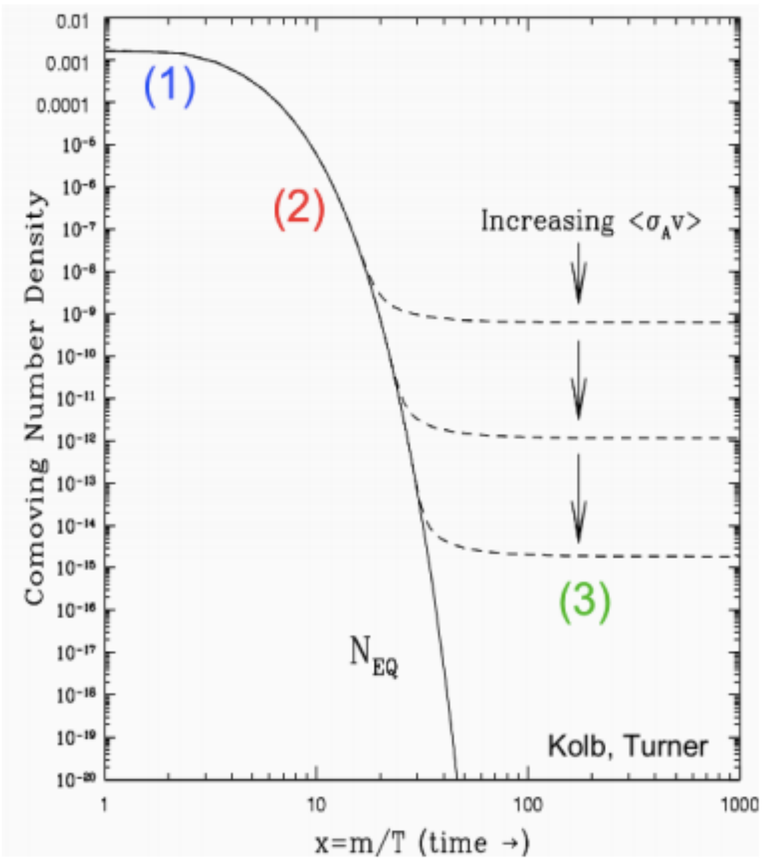
DM-T
D. Cerdeño lessons



Some well motivated candidates

- Axions
- Sterile neutrinos
- WIMPs
  - SUSY
  - Kaluza Klein
  - Little Higgs
  - ……

Dark Matter Candidates: WIMPs



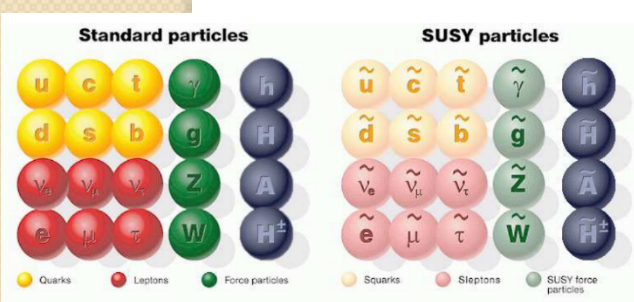
If DM particle was in thermal equilibrium in the primordial soup at freeze out the annihilation cross section determined the relic abundance

WIMPs are convenient DM candidates

WIMP MIRACLE -> electroweak scale cross sections for a GeV particle produce the correct Ωc

WIMP Candidates

Supersymmetry



Conservation of R parity implies that the Lightest Supersymmetric Particle LSP is stable -> DM !!

Minimal Supersymmetric Standard Model MSSM

Standard Model particles and their superpartners in the MSSM (adapted from Ref. [203])

Standard Model particles and fields		Supersymmetric partners			
		Interaction eigenstates		Mass eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = d, c, b, u, s, t$	Quark	$\tilde{q}_L, \tilde{q}_R$	Squark	$\tilde{q}_1, \tilde{q}_2$	Squark
$l = e, \mu, \tau$	Lepton	$\tilde{l}_L, \tilde{l}_R$	Slepton	$\tilde{l}_1, \tilde{l}_2$	Slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	Neutrino	$\tilde{\nu}$	Sneutrino	$\tilde{\nu}$	Sneutrino
g	Gluon	$\tilde{g}$	Gluino	$\tilde{g}$	Gluino
$W^\pm$	W-boson	$\tilde{W}^\pm$	Wino		
H^-	Higgs boson	$\tilde{H}_1^-$	Higgsino	$\tilde{\chi}^\pm_{1,2}$	Chargino
H^+	Higgs boson	$\tilde{H}_2^+$	Higgsino		
B	B-field	$\tilde{B}$	Bino		
W^3	W^3-field	$\tilde{W}^3$	Wino		
H_1^0	Higgs boson			$\tilde{\chi}^0_{1,2,3,4}$	Neutralino
H_2^0	Higgs boson	$\tilde{H}_1^0$	Higgsino		
H_3^0	Higgs boson	$\tilde{H}_2^0$	Higgsino		

The most likely LSP is the lightest neutralino

Kaluza Klein Theories

Extra dimensions are assumed to be compactified

-> new symmetry with a momentum number conservation

The lightest KK particle LKP is stable and cannot decay into standard model particles -> Convenient DM candidate!!

and more...

Other Candidates

Axions or ALPs

Axion would solve the strong CP problem

Is the boson associated to a global U(1) symmetry spontaneously broken

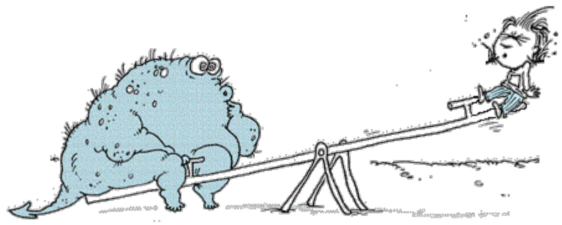
Pseudoscalar
Very light
Neutral

ALPS Axion Like Particles are the Nambu Goldstone bosons associated to the breaking of any U(1) symmetry

Although are nonthermally produced they behave as CDM

Sterile Neutrinos

Sterile neutrinos (Ni) are a natural ingredient of the most popular mechanism to generate neutrino masses the seesaw mechanism



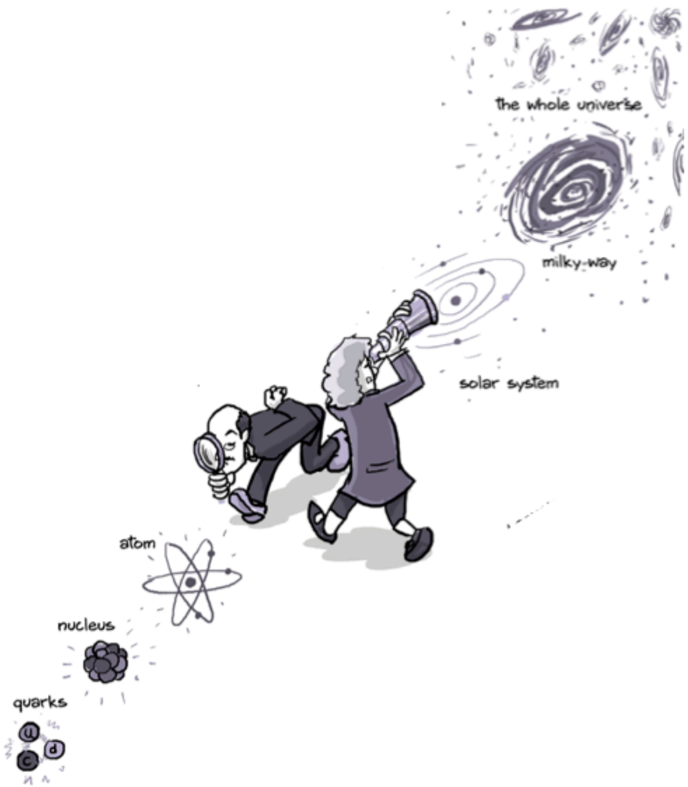
Sterile neutrinos are neutral leptons with no ordinary weak interactions except those induced by mixing with active neutrinos

But could have interactions involving new physics

The Dark Matter challenge

DM detection is a difficult task

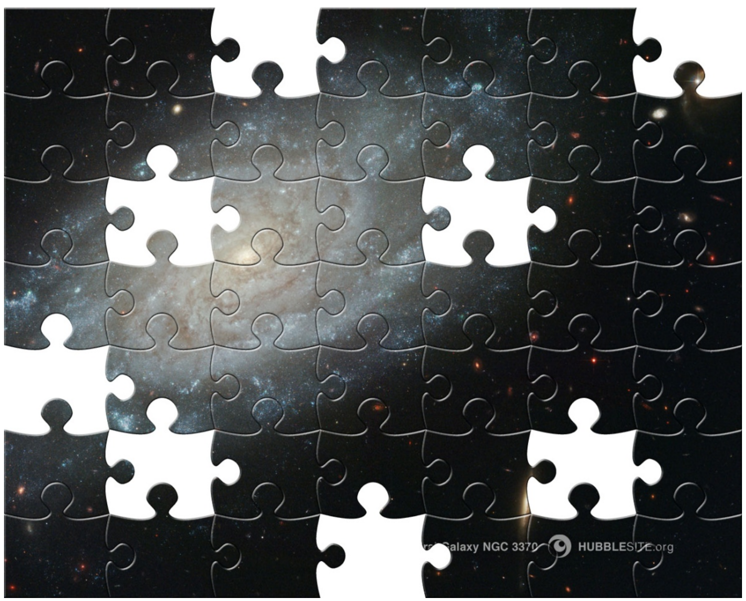
Challenge for:



Astrophysics
Cosmology
Particle Physics
Nuclear Physics
Detector Physics
...

The Multimessenger Approach

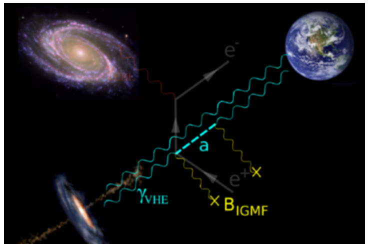
To decouple unknown and uncertainties in such a challenge for experimental detection



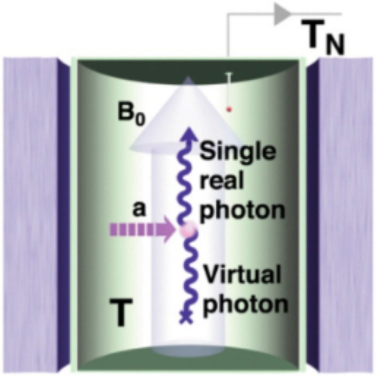
- Multimessenger approach (direct vs indirect)
- Multitarget and multi-technique strategy

AXION Searches

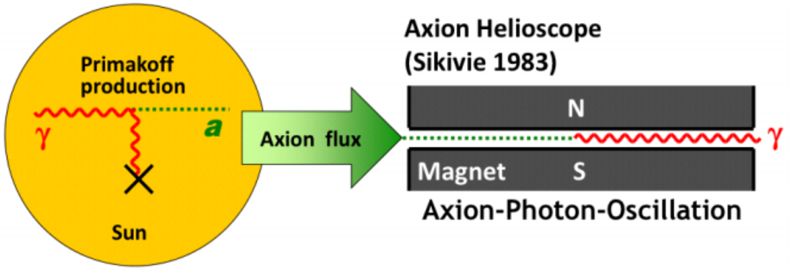
- Astrophysical hints for axions/ALPs
  - Observation of gamma rays from from distant sources (VHE transparency)
  - Anomalous cooling of white dwarfs



- Relic Axions part of galactic DM halo
  - Axion Haloscopes ADMX

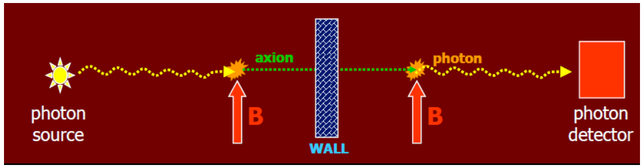


- Solar Axions Look for axions produced in the Sun by Primakoff conversion of photons
  - Crystal detectors
  - Axion Helioscopes CAST IAXO



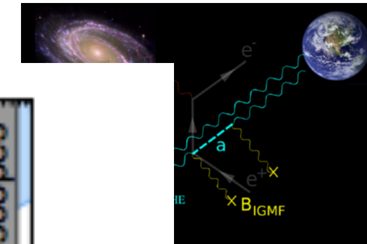
- Axions in the lab
  - Laser experiments ("Light shinning through wall")
  - Vacuum birrefringence experiments

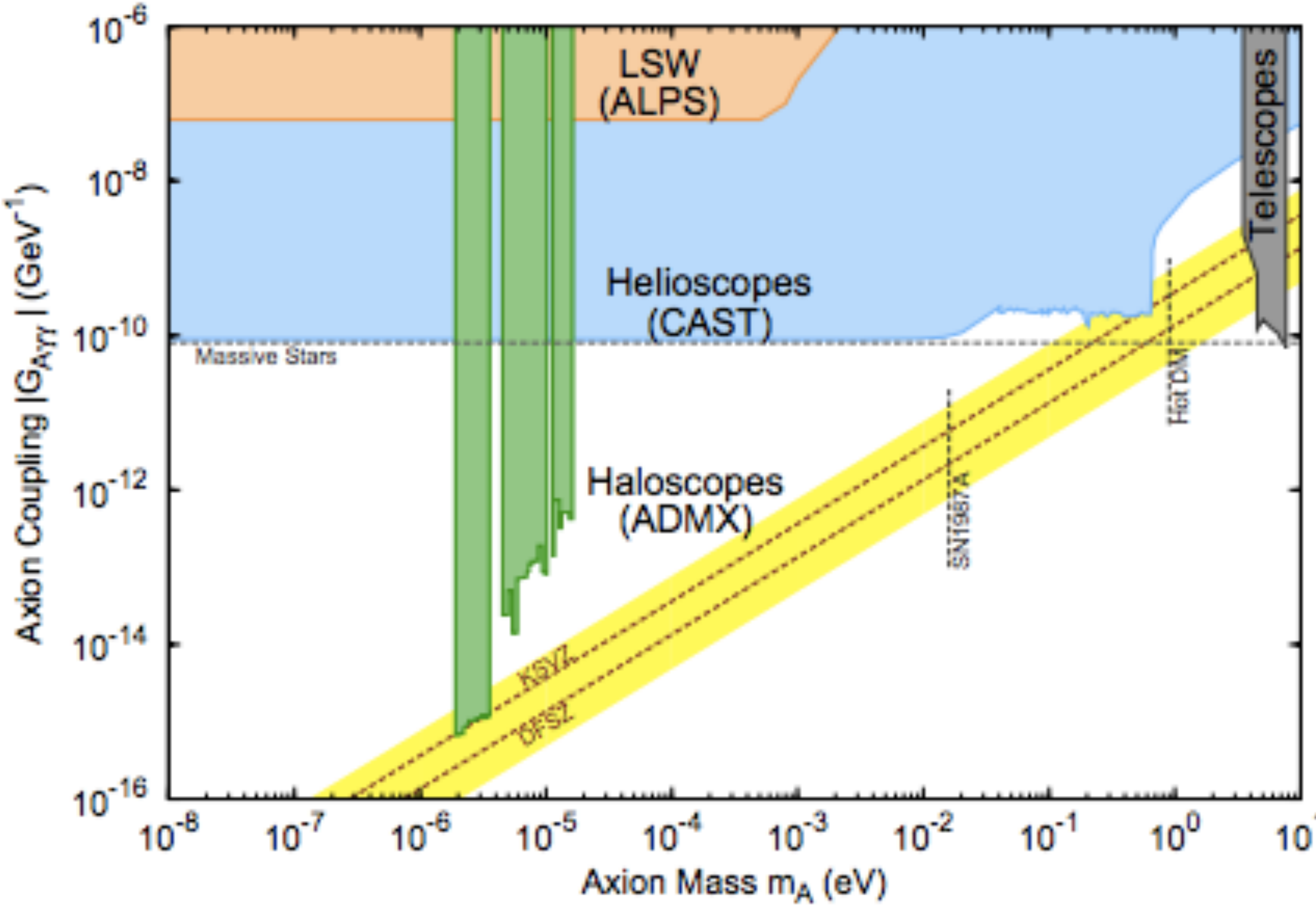
ALPS II OSQAR



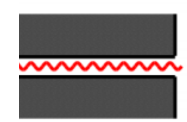
Axion Searches

- Astrophysical hints for axions ALPs



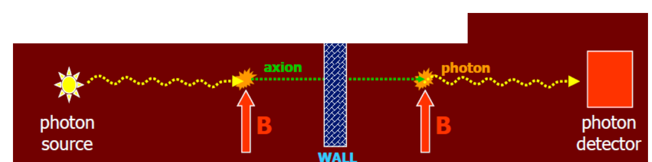


- R
- S
  P

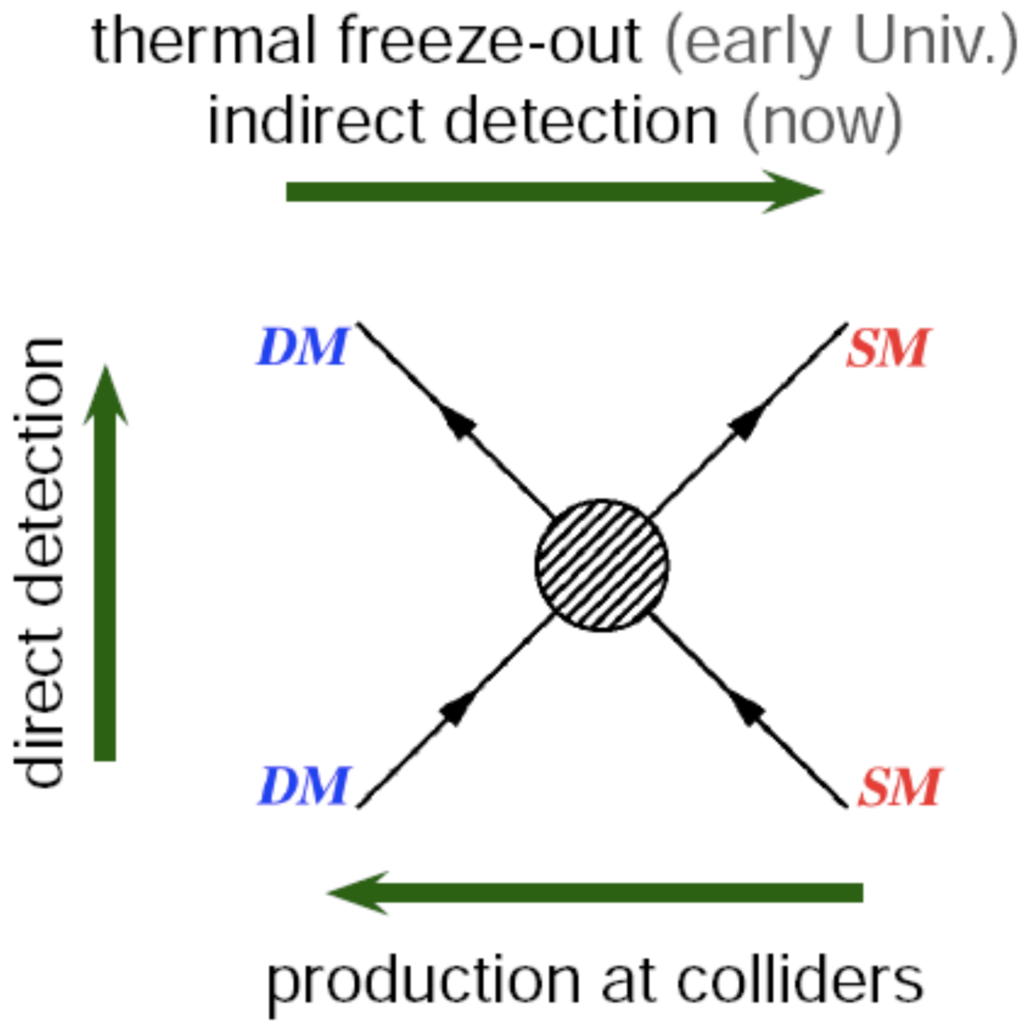


- A
  - Vacuum birrefringence experiments

    ALPS II OSQAR

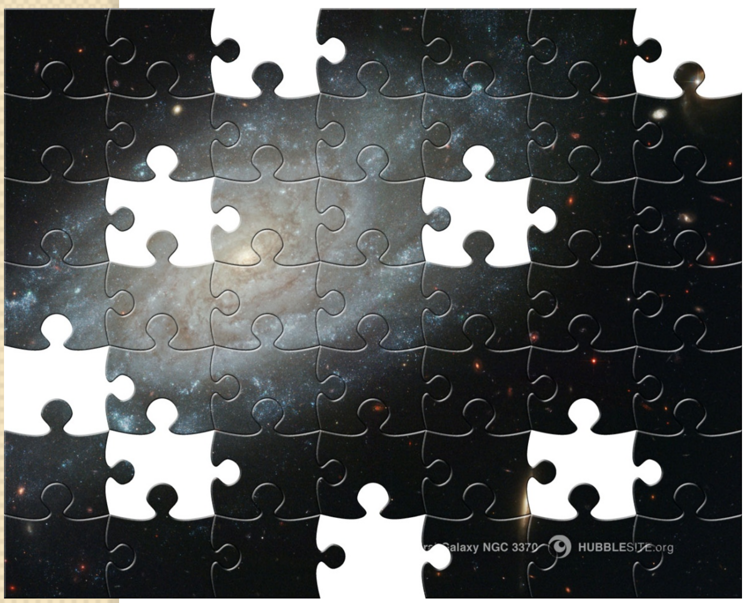


WIMPs detection



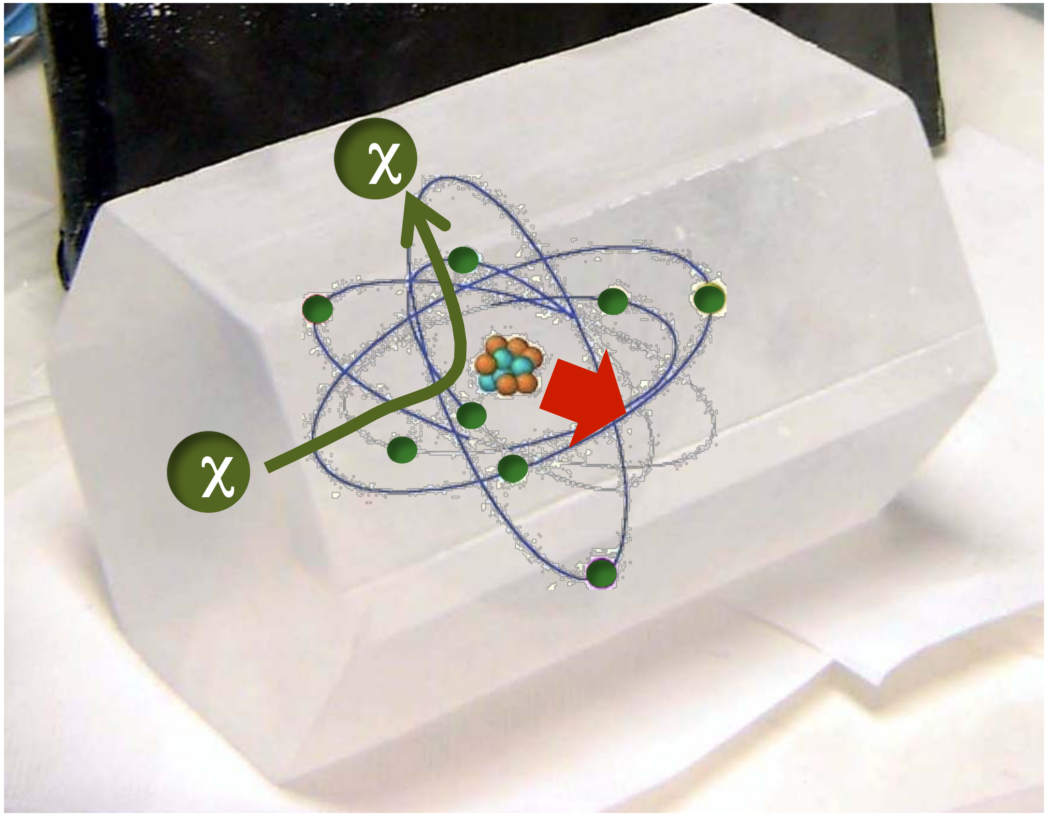
Very few assumptions needed: unknown mass and weak cross section

OUTLINE



- Direct Detection of DM
  - Expected signal
  - Detection Mechanisms
  - Review of experimental status
- Indirect Detection of DM
  - Search Strategy
  - Review of experimental status

WIMP Direct Detection



We place in a convenient laboratory one of our detectors and we wait till WIMPs interact with it

WIMP Direct Detection

How do WIMPs interact?

How do we see the interaction?

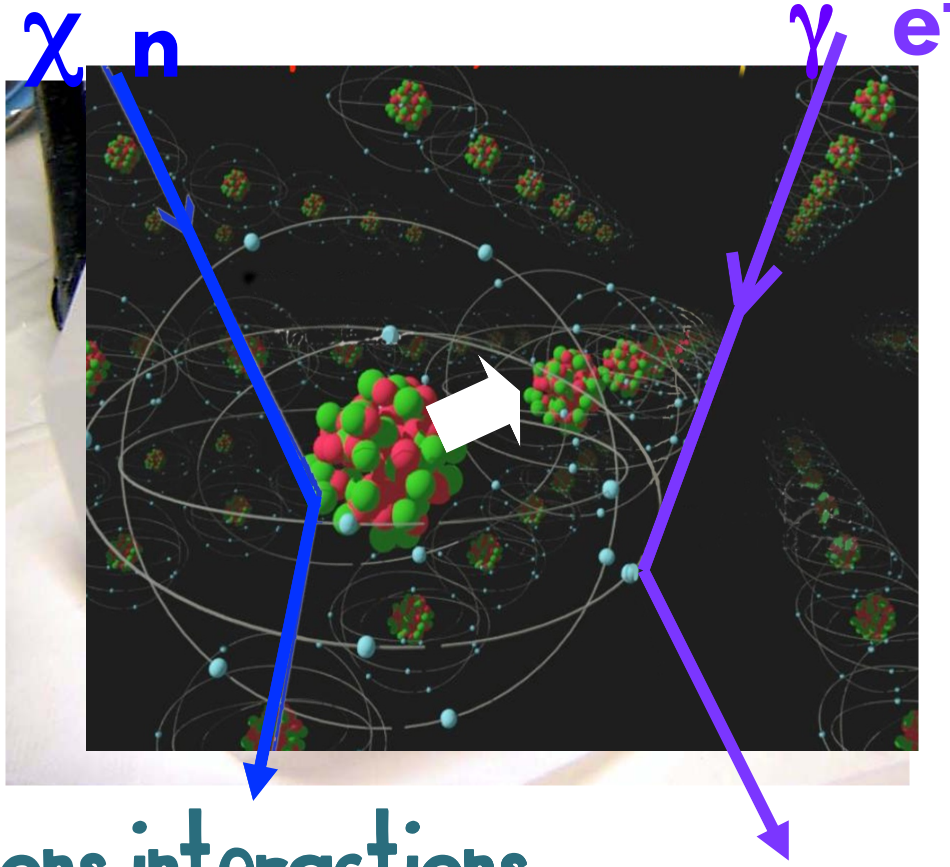
What interferences can be expected in this detection?

We place in a convenient laboratory one of our detectors and we wait till WIMPs interact with it

WIMP Direct Detection

How do WIMPs interact?

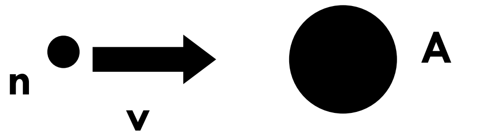
They are suppossed to produce NUCLEAR RECOILS by elastic scattering off nuclei



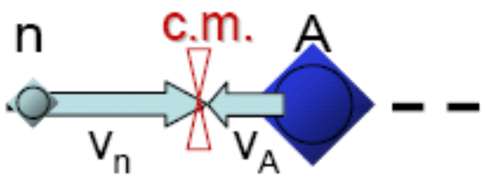
Similar to neutrons interactions

We place in a convenient laboratory one of our detectors and we wait till WIMPs interact with it

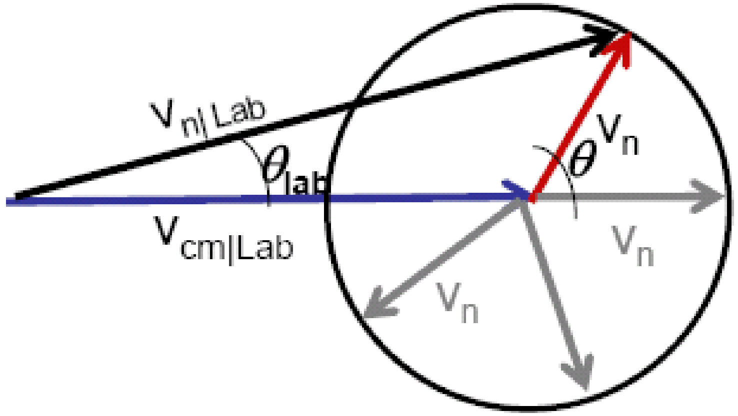
Kinematics of elastic scattering



$$v_{cm|Lab} = v \frac{1}{A+1}$$



$$v_n = v \frac{A}{A+1} \qquad v_A = -v \frac{1}{A+1}$$

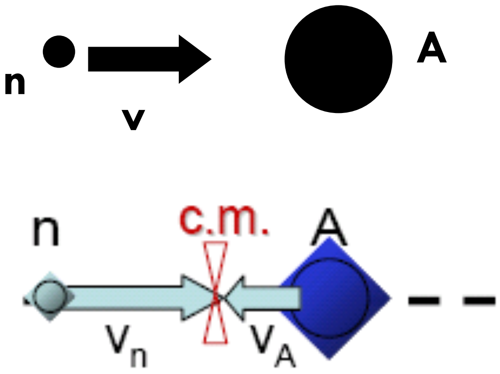


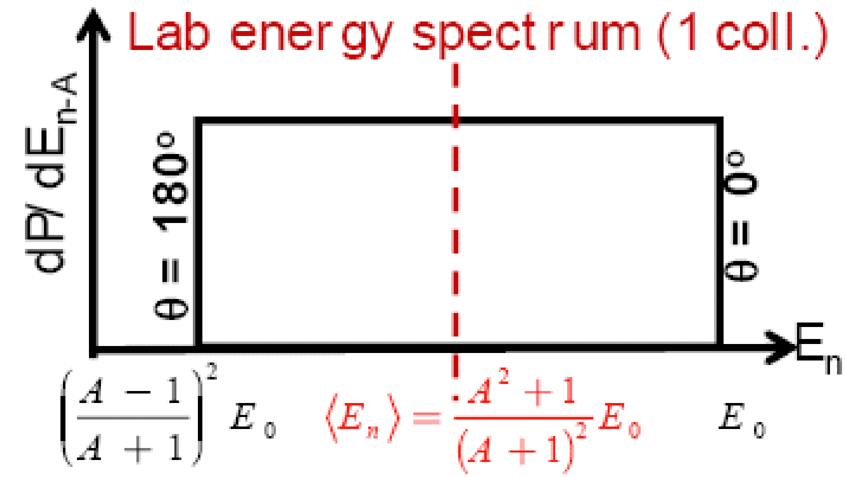
$$v_{CM} - v_n < v_n^f < v_{CM} + v_n$$

$$-\frac{A-1}{A+1} v < v_n^f < v$$

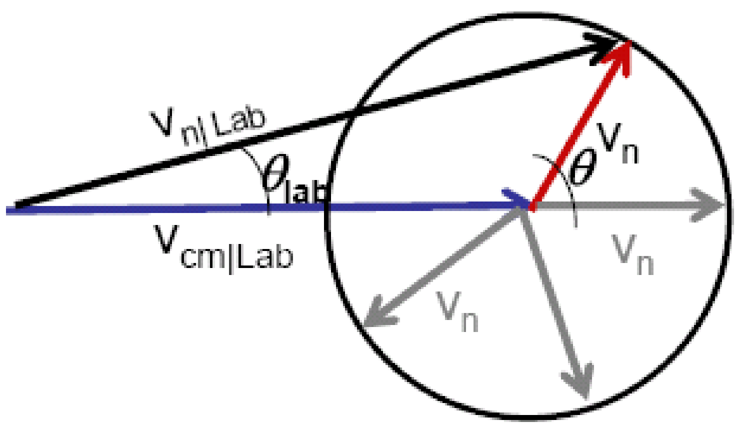
$$\left(\frac{A-1}{A+1}\right)^2 E_0 < E_n^f < E_0$$

Kinematics of elastic scattering





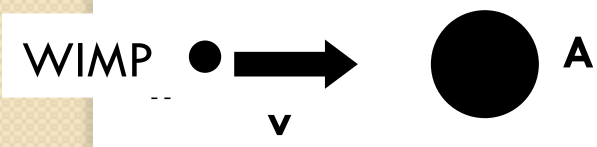
$$E_n^f \propto \left(\vec{v}_{CM} + \vec{v}_n\right)^2 = \frac{v^2(1+A^2)}{(A+1)^2} + \frac{2v^2 A}{(A+1)^2}\cos\theta$$

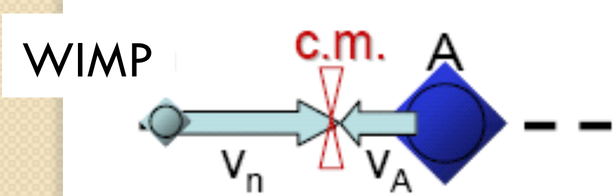


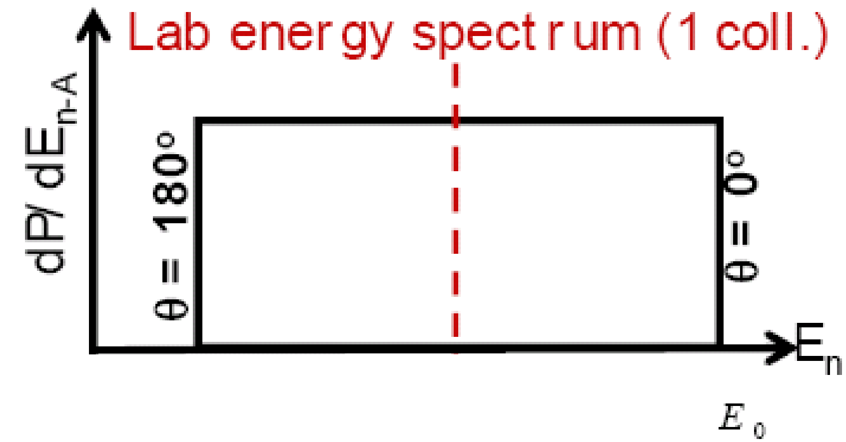
$$\frac{dE_n^f}{d\theta} \propto \sin\theta \qquad \frac{dE_n^f}{d\Omega} \propto CONSTANT$$

$$\left(\frac{A-1}{A+1}\right)^2 E_0 < E_n^f < E_0$$

Kinematics of elastic scattering







$$E^{f}_{WIMP} \propto \left(\vec{v}_{CM} + \vec{v}_{W}\right)^2 = \frac{v^2 (m_w^2 + M_N^2)}{(m_w + M_N)^2} + \frac{2v^2 m_w M_N}{(m_w + M_N)^2} \cos\theta$$

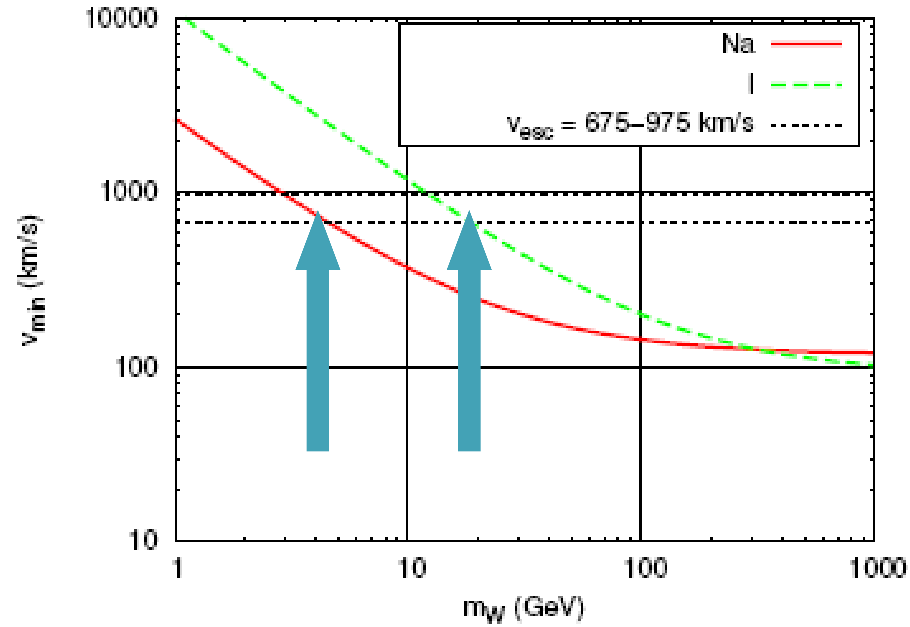
$$T_{recoil} = E_0 - E^{f}_{WIMP} = \frac{m_W{}^2 M_N}{(m_W + M_N)^2} v^2 \left(1 - \cos\theta\right)$$

$$T_{\max} = \frac{2 m_W{}^2 M_N}{(m_W + M_N)^2} v^2$$

Kinematical mass matching

Kinematics of elastic scattering

$T_{threshold}$ 2 keVee in NaI target



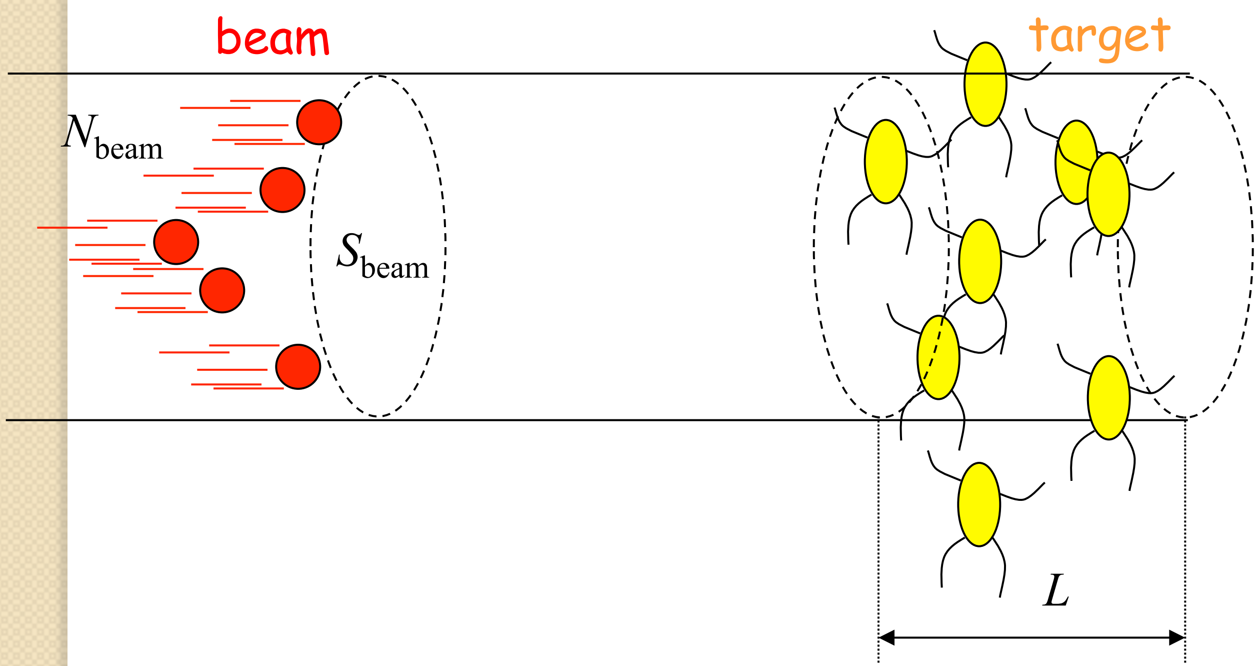
$$v_{\min}{}^2 = \frac{(m_W + M_N)^2}{2m_W{}^2 M_N} T_{threshold}$$

The whole WIMP phase space is not accesible

$$T_{\max} = \frac{2m_W{}^2 M_N}{(m_W + M_N)^2} v^2$$

Kinematical mass matching

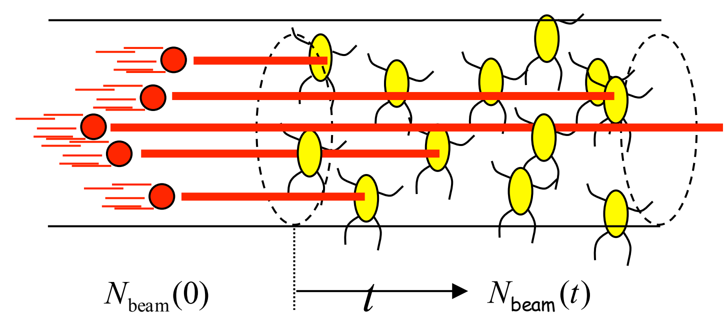
Dark Matter Interaction Rate



Assuming targets do not help or screen each other

$$N_{int} = j_{beam}\,\sigma\,N_{blanco} = N_{beam}\,\sigma\,n_{blanco}\,L$$

But targets screen each other

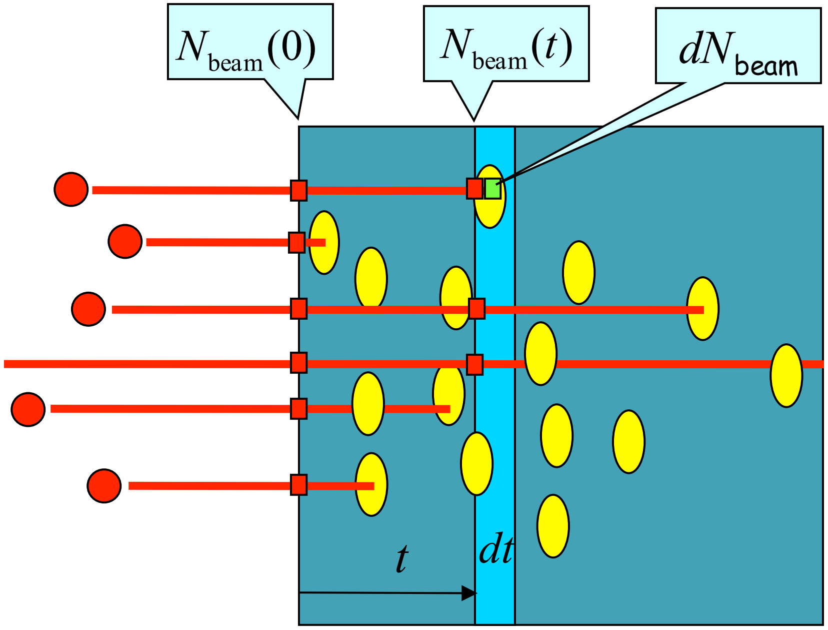


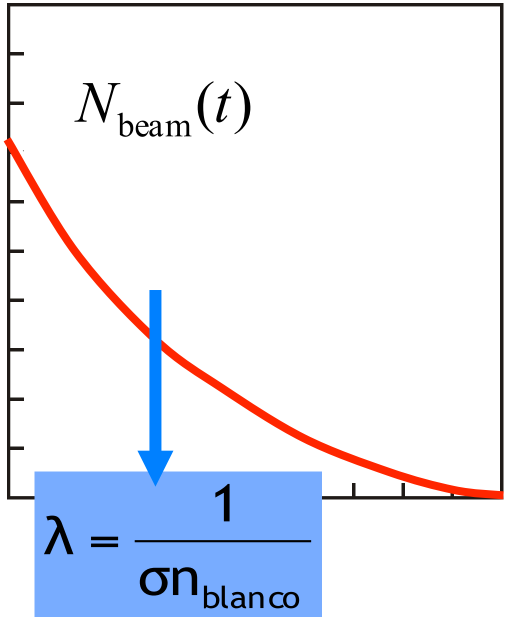
Dark Matter Interaction Rate

Interaction probability for Dark Matter particles is unknown -> σ

$$dN_{beam} = -N_{beam}\, \sigma\, n_{blanco}\, dt$$

$$\frac{dN_{beam}(t)}{dt} = -N_{beam}(t)\, \sigma\, n_{blanco}$$



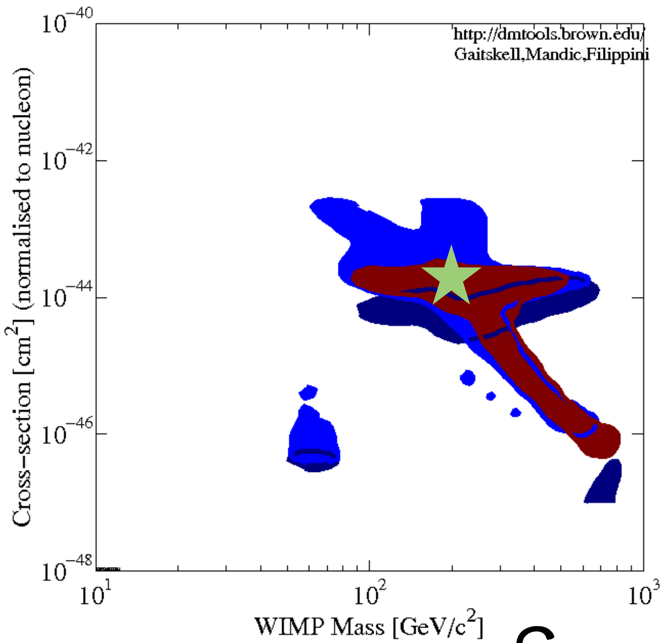


$$N_{beam}(t) = N_{beam}(0)\, e^{-\sigma n_{blanco} t}$$

Dark Matter Interaction Rate

Interaction probability for Dark Matter particles is unknown -> σ(WIMP-proton)

Assuming a neutralino SUSY candidate



λ of about a light year!!!

Screening is negligible at detector scales

Matter is transparent

Dark Matter Interaction Rate

$$N_{int} = j_{beam}\,\sigma\,N_{blanco} = N_{beam}\,\sigma\,n_{blanco}\,L$$

$$R = \frac{dN_{int}}{dt} = \Phi_{WIMPs} N_N \sigma_{WIMP-N} = n_{WIMPs}\, v\, N_N \sigma_{WIMP-N}$$

$$\frac{dR}{dE_R} = n_{WIMPs}\, v\, N_N \frac{d\sigma_{WIMP-N}}{dE_R}$$

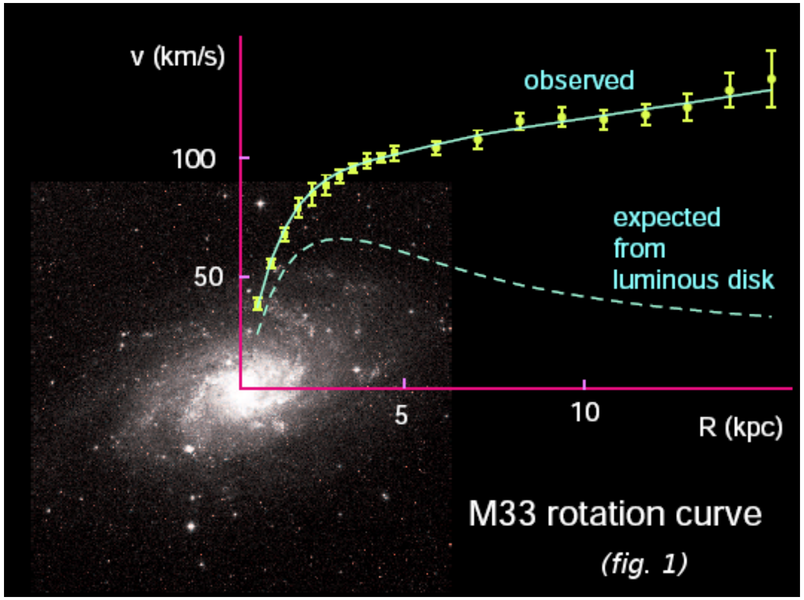
Differential rate
recoil energy
dependence

$$N_N = \frac{M_{det}}{M_N}$$

Target
Nuclear and Particle models

Dark Matter Halo model

Dark Matter Galactic Haloes



Rotation Velocity Curves hint at the presence of Dark Haloes around galaxies

What about Dark Matter in our galaxy?

nature physics

LETTERS

PUBLISHED ONLINE: 9 FEBRUARY 2015 | DOI: 10.1038/NPHYS3237

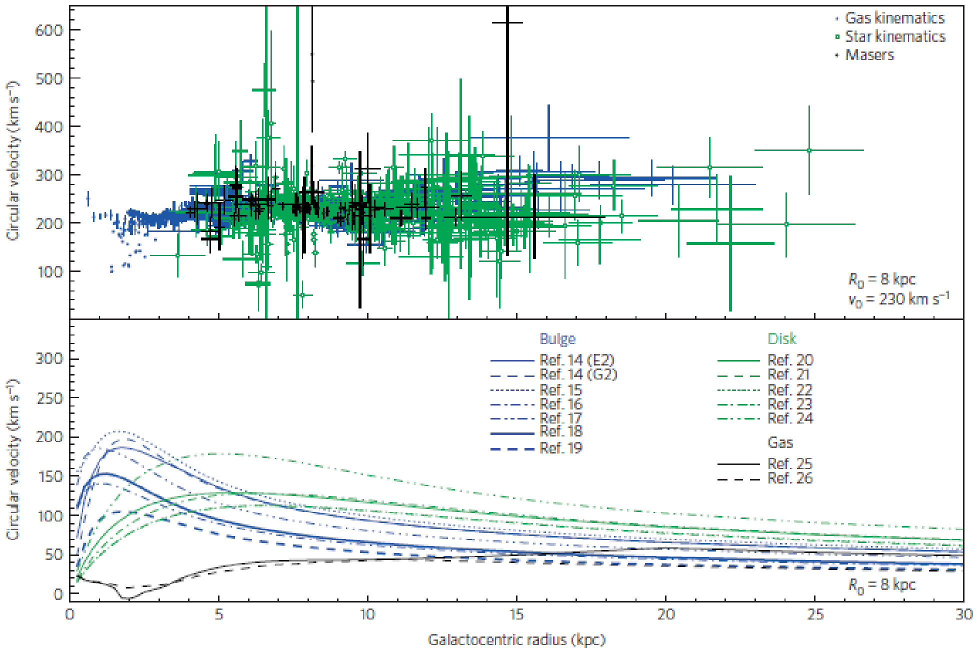
Evidence for dark matter in the inner Milky Way

Fabio Iocco[1,2]*, Miguel Pato[3,4] and Gianfranco Bertone[5]

TASK 3

The ubiquitous presence of dark matter in the Universe is today a central tenet in modern cosmology and astrophysics[1]. Throughout the Universe, the evidence for dark matter is compelling in dwarfs, spiral galaxies, galaxy clusters as well as at cosmological scales. However, it has been historically difficult to pin down the dark matter contribution to the total mass density in the Milky Way, particularly in the innermost regions of the Galaxy and in the solar neighbourhood[2]. Here we present an up-to-date compilation of Milky Way rotation curve measurements[3-13], and compare it with state-of-the-art baryonic mass distribution models[14-26]. We show that current data strongly disfavour baryons as the sole contribution to the Galactic mass budget, even inside the solar circle. Our findings demonstrate the existence of dark matter in the inner Galaxy without making any assumptions about its distribution. We anticipate that this result will compel new model-independent constraints on the dark matter local density and profile, thus reducing uncertainties on direct and indirect dark matter searches, and will help reveal the structure and evolution of the Galaxy.

Evidence for Dark Matter in the inner Milky Way



Milky Way Rotation Velocity Curve

Figure 1 | The rotation curve of the Milky Way. In the top panel we show our compilation of rotation curve measurements as a function of Galactocentric radius, including data from gas kinematics (blue dots; HI terminal velocities, CO terminal velocities, HI thickness, HII regions, giant molecular clouds), star kinematics (open green squares; open clusters, planetary nebulae, classical cepheids, carbon stars) and masers (open black circles). Error bars correspond to 1σ uncertainties. The bottom panel shows the contribution to the rotation curve as predicted from different models for the stellar bulge (blue), stellar disk (green) and gas (black). We assume a distance to the Galactic Centre $R_0 = 8$ kpc in both panels, and a local circular velocity $v_0 = 230$ km s^{-1} in the top panel.

nature physics

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Evidence for Dark Matter in the inner Milky Way

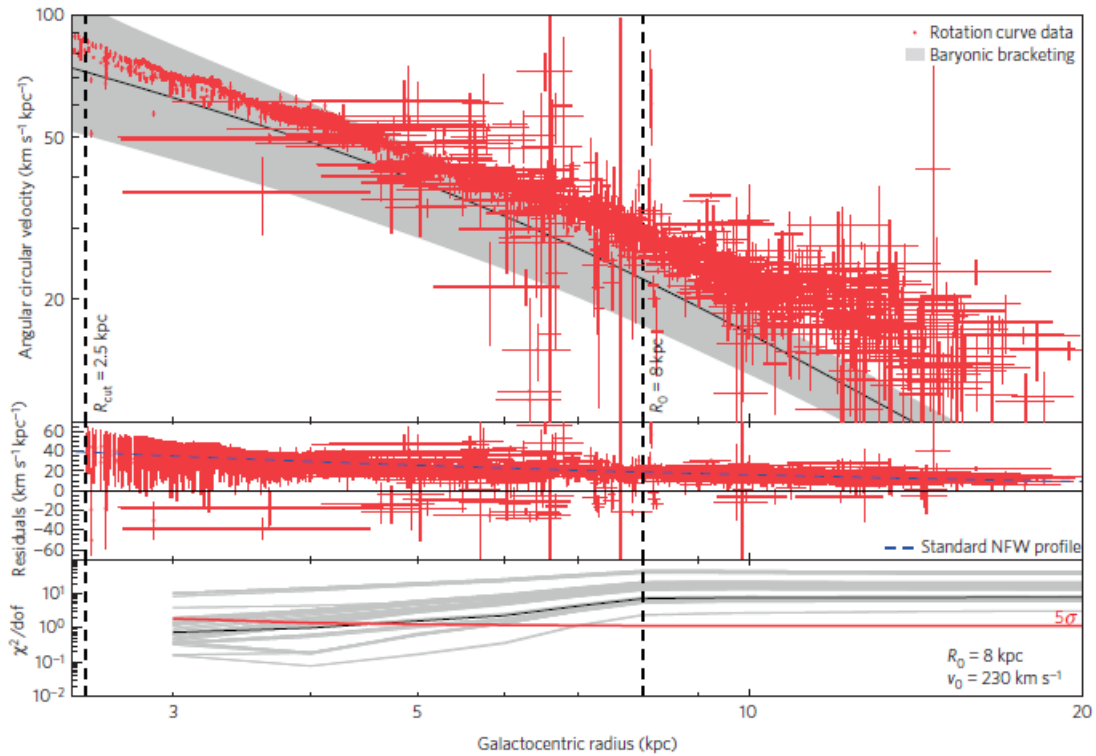

Figure 2 | Evidence for dark matter. In the top panel we show the angular velocity measurements from the compilation shown in Fig. 1 (red dots) together with the bracketing of the contribution of all baryonic models (grey band) as a function of Galactocentric radius. Error bars correspond to 1σ uncertainties, and the grey band shows the envelope of all baryonic models including 1σ uncertainties. The contribution of a fiducial baryonic model is marked with the black line. The residuals $(\omega_c^2-\omega_b^2)^{1/2}$ between observed and predicted angular velocities for this baryonic model are shown in the central panel. The blue dashed line shows the contribution of a Navarro-Frenk-White profile with scale radius of 20 kpc normalized to a local dark matter density of 0.4 GeV cm^{-3}. The bottom panel shows the cumulative reduced χ^2 for each baryonic model as a function of Galactocentric radius. The black line shows the case of the fiducial model plotted in black in the top panel, and the thick red line represents the reduced χ^2 corresponding to 5σ significance. In this figure we assume a distance to the Galactic Centre $R_0=8$ kpc and a local circular velocity $v_0=230$ km s^{-1}, and we ignore all measurements below $R_{cut}=2.5$ kpc.

TTERS
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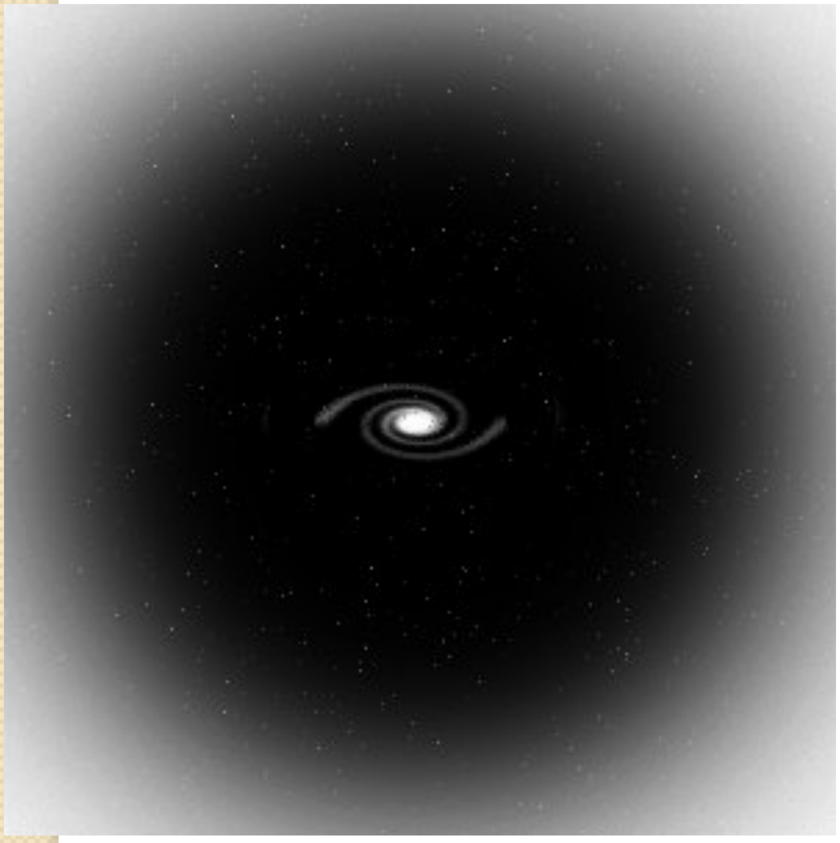
Evidence for dark matter in the inner Milky Way

Fabio Iocco[1,2]*, Miguel Pato[3,4] and Gianfranco Bertone[5]

Milky Way Dark Halo



Milky Way Rotation Velocity Curve determines halo mass density but not particle number density

$$n_W = \frac{\rho_0}{m_W}$$

$\rho_0 \approx 0.2\text{-}0.4$ GeV/cm^3
~ 5 10^{-22} g/dm^3

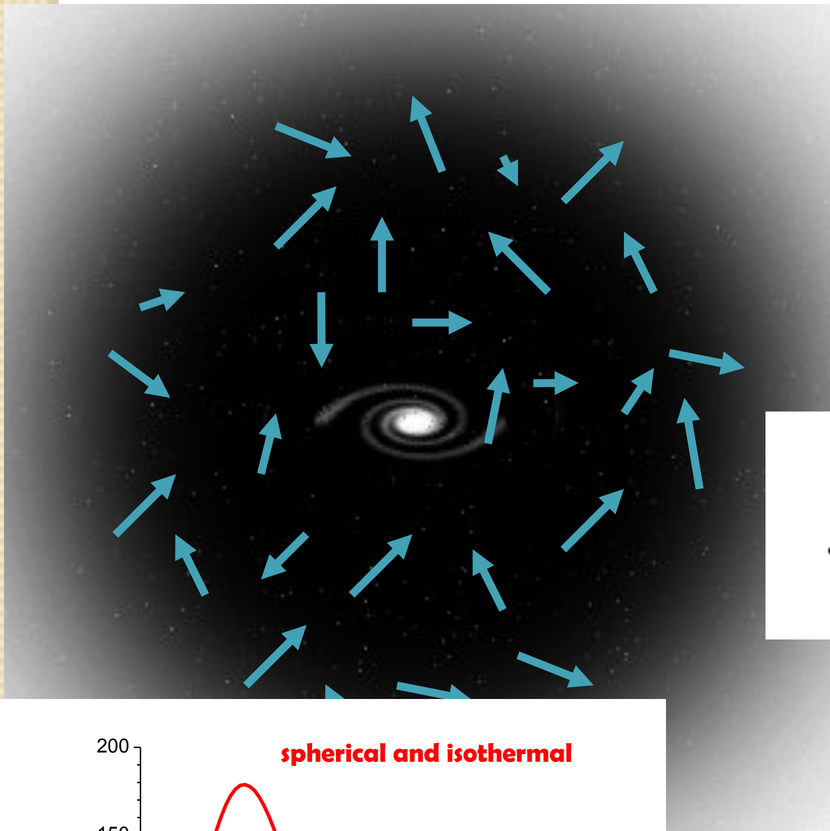
~ 300 protons/dm^3

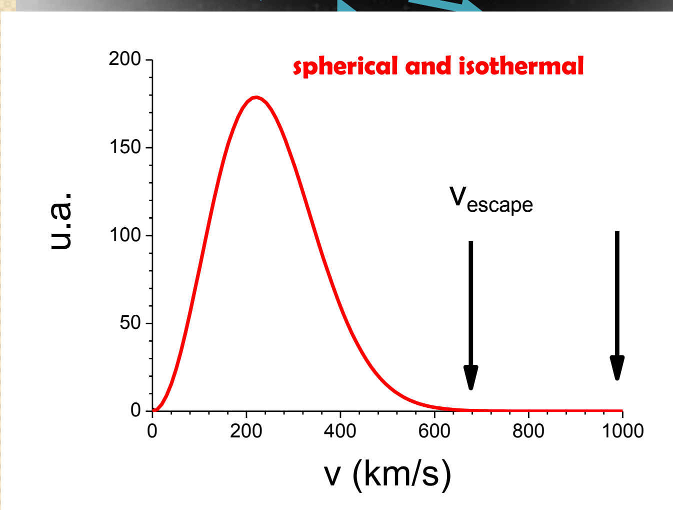
Unknown particle mass

If $m_w \approx 100$ GeV

$n_W \approx 3$ WIMPs/dm^3

Milky Way Dark Halo





The most simple model isotropic and spherical thermal distribution of non relativistic WIMPs

$$f(\vec{v}_{gal})d^3\vec{v}_{gal} = \frac{1}{v_0^3\pi^{3/2}} e^{-\frac{|\vec{v}_{gal}|^2}{v_0^2}} d^3\vec{v}_{gal}$$

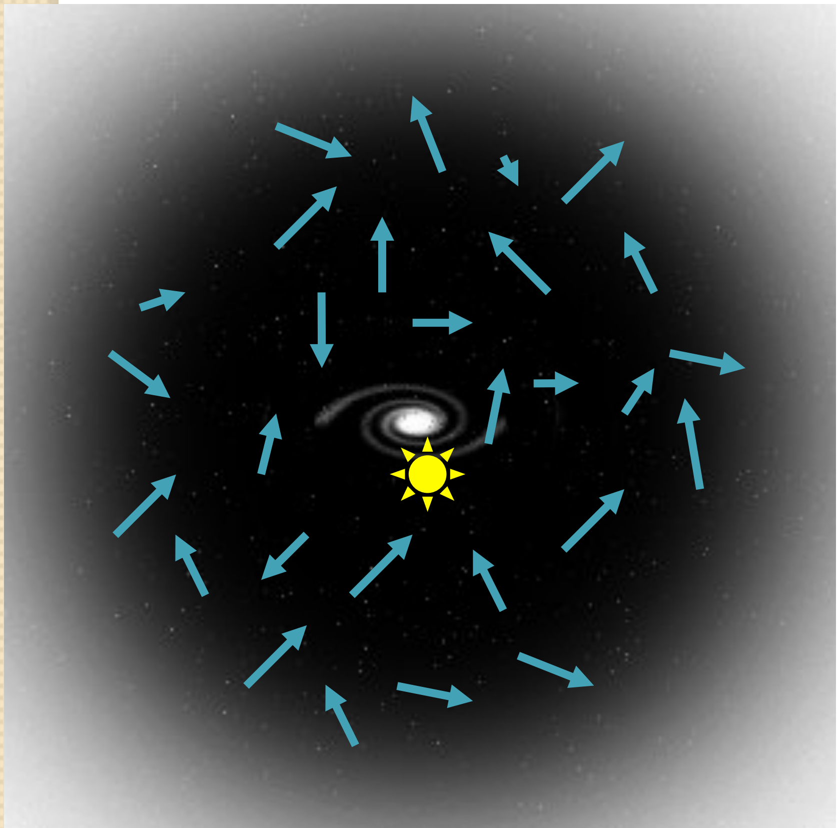
$v_{rms} \approx$ 270km/s–300km/s

$v_0 = (2/3)^{1/2}$ vrms

$v_{esc} \approx$ 600 km/s

$$E_r^{max} = \frac{1}{2} m_W c^2 \left(\frac{v}{c}\right)^2 \approx \frac{1}{2} m_W 10^{-6} \approx \frac{1}{2}(m_W / GeV)keV$$

The WIMP Flux at the Earth Position



The Earth moves in the DM halo accompanying the Sun around the galaxy

WIMP WIND

- -Directionality
- -Annual modulation in the rate

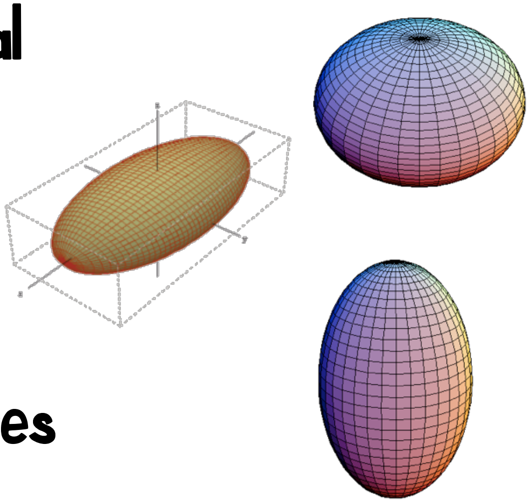
$\rho_0 \approx 0.2\text{-}0.4$ GeV/cm^3

If $m_w \approx 1$ GeV – 10 TeV

$\Phi_{WIMPs} \approx 10^4\text{-}10^8$ s^{-1} cm^{-2}

Milky Way Dark Halo

Haloes can be non spherical: triaxial, ellipsoidal

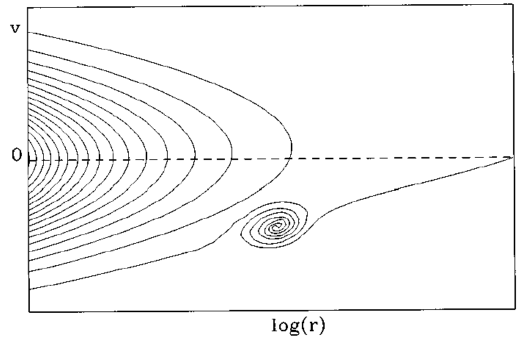


Haloes can have sub-structure:

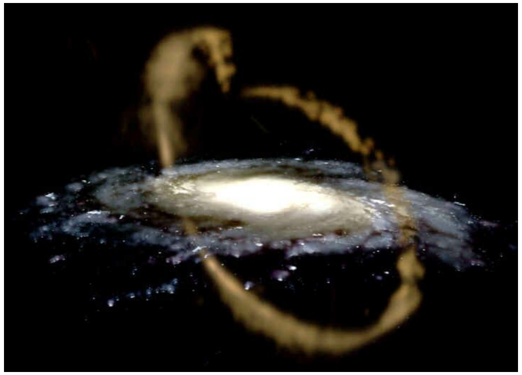
- Sub haloes
- Caustic Rings
- Satellites producing directional fluxes

Sub haloes

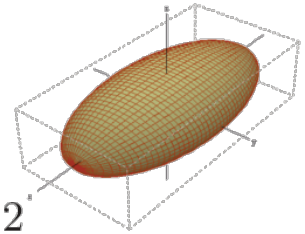
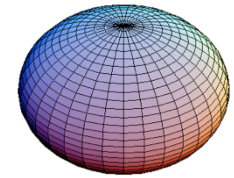
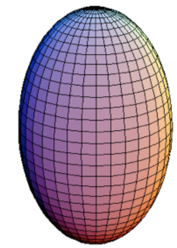
Caustic Rings



Satellite galaxies

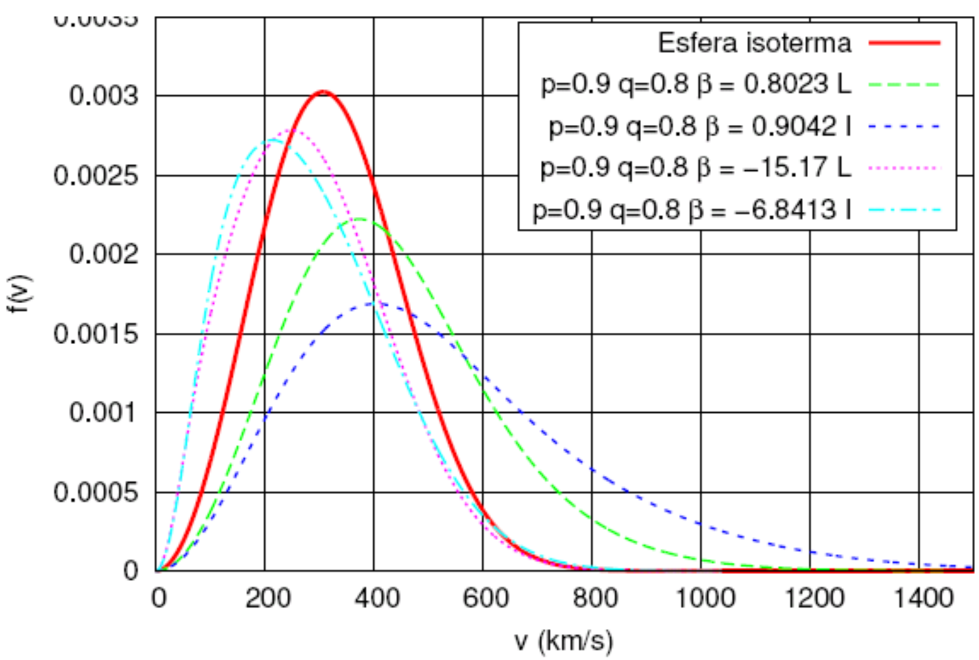


Haloes can be non spherical: triaxial, ellipsoidal

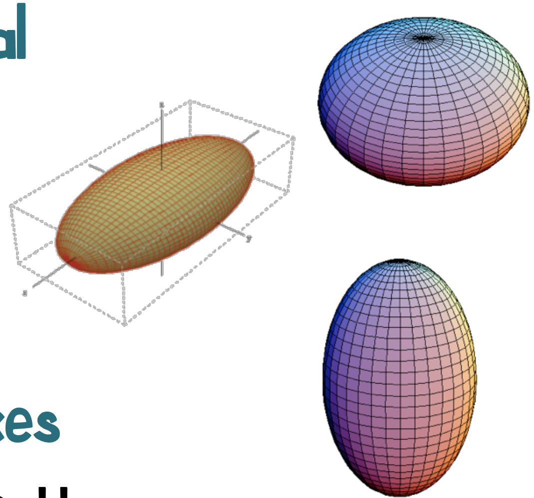
Ellipsoidal Halo Model

$$f(\vec{v}) = \frac{1}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} exp[-\frac{v_x^2}{2\sigma_x^2} - \frac{v_y^2}{2\sigma_y^2} - \frac{v_z^2}{2\sigma_z^2}]$$



Milky Way Dark Halo

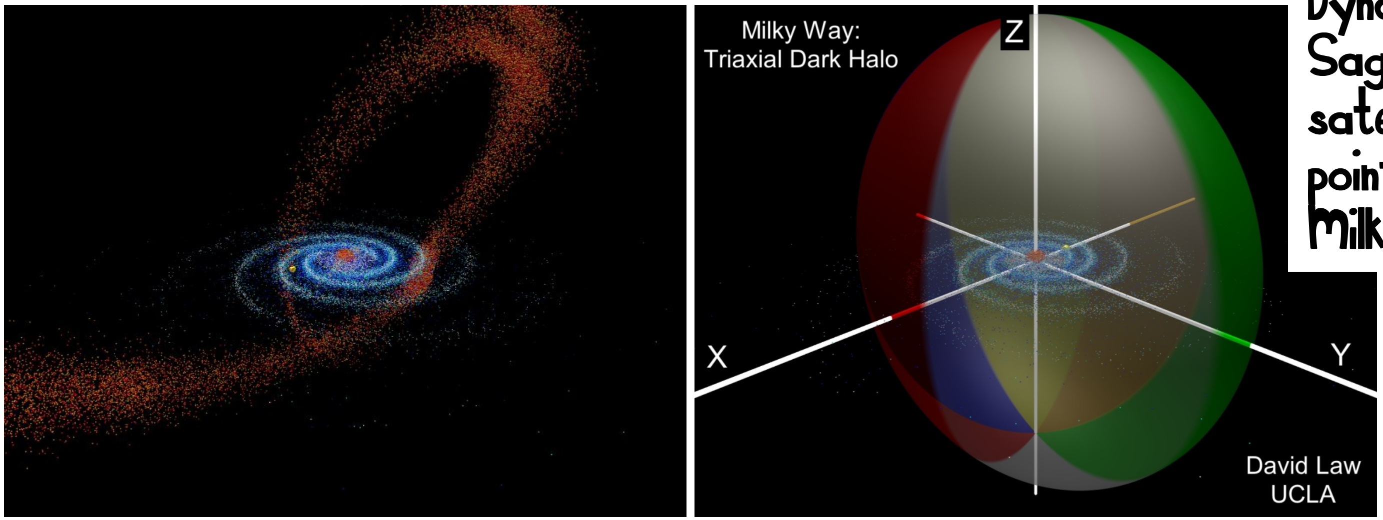
Haloes can be non spherical: triaxial, ellipsoidal



Haloes can have sub-structure:

- Sub haloes
- Caustic Rings
- Satellites producing directional fluxes

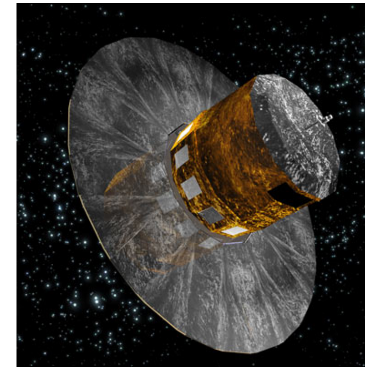
Sagittarius Dwarf satellite galaxy could produce a Dark Matter directional flux near the Solar System



Dynamics from Sagittarius Dwarf satellite galaxy points to triaxial Milky Way Halo

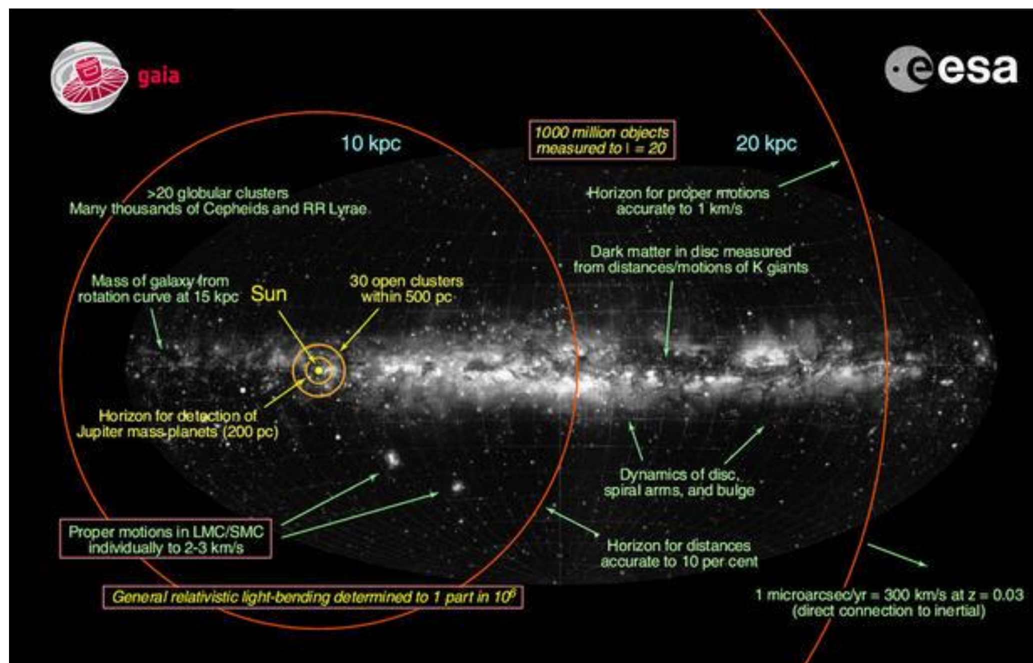
GAIA Mission

19 December 2013 launch by ESA



mission to chart a three dimensional map of the Milky Way.

Unprecedented positional and radial velocity measurements with the accuracies needed to produce a stereoscopic and kinematic census of about one billion stars in our Galaxy and throughout the Local Group.



Dark Matter Interaction Rate

$$N_{int} = j_{beam}\,\sigma\,N_{blanco} = N_{beam}\,\sigma\,n_{blanco}\,L$$

$$R = \frac{dN_{int}}{dt} = \Phi_{WIMPs} N_N \sigma_{WIMP-N} = n_{WIMPs}\, v\, N_N \sigma_{WIMP-N}$$

$$\frac{dR}{dE_R} = n_{WIMPs}\, v\, N_N \frac{d\sigma_{WIMP-N}}{dE_R}$$

Differential rate recoil energy dependence

$$N_N = \frac{M_{det}}{M_N}$$

$$n_W = \frac{\rho_0}{m_W}$$

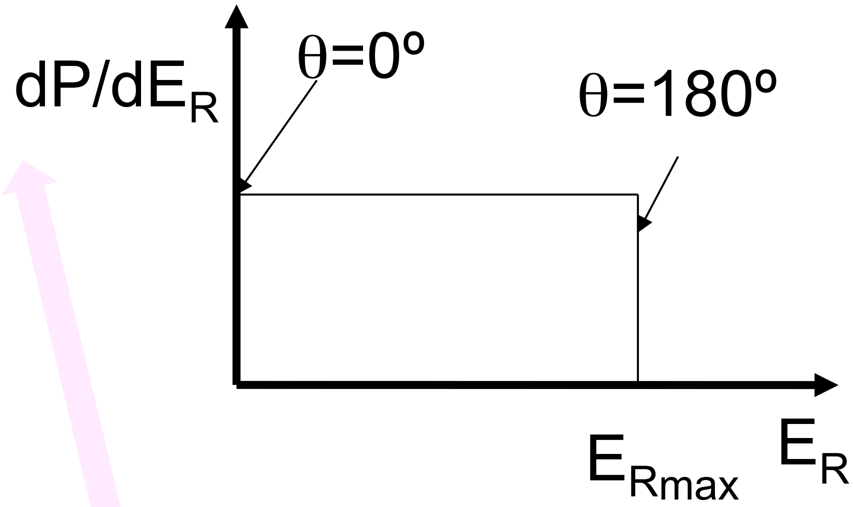
Target Nuclear and Particle models

$$\frac{dR}{dE_R} = n_{WIMPs}\, N_N \int f(v)\, v\, \frac{d\sigma_{WIMP-N}}{dE_R}\, dv$$

Dark Matter Interaction Rate

$$\frac{d\sigma_{WIMP-N}}{dE_R} = \frac{\sigma_{WIMP-N}}{E_{Rmax}}$$

$$E_{Rmax} = \frac{2m_W^2 M_N}{(m_W + M_N)^2} v^2$$



Target
Nuclear and Particle models

$$\frac{dR}{dE_R} = n_{WIMPs} N_N \int f(v)\, v \frac{d\sigma_{WIMP-N}}{dE_R} dv$$

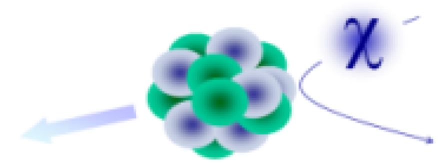
Dark Matter Interaction Rate

$$\frac{dR}{dE_R} = \frac{\rho_0 M_{det}}{2 m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv^3 \sigma_{WIMP-N}$$

WIMP-nucleus interaction

But ... WIMPs interacts at more fundamental level with quarks

NUCLEAR FORM FACTORS are required



WIMP MODEL
NUCLEAR MODEL

Dark Matter Interaction Rate

$$\frac{dR}{dE_R} = \frac{\rho_0 M_{det}}{2 m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv^3 \left(\sigma_{SI}^0 F_{SI}^2 + \sigma_{SD}^0 F_{SD}^2 \right)$$

COHERENT INTERACTION

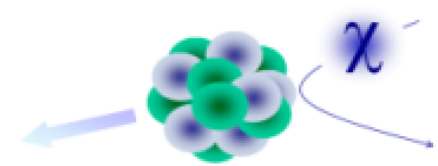
SPIN DEPENDENT INTERACTION

WIMP-nucleus interaction

To compare experiments!!!

-Work on point like cross sections

-Normalize to nucleon cross sections



$$\sigma_{SI}^0 \propto \frac{m_{WN}^2}{m_{Wn}^2} A^2 \sigma_{SI}^{nucleón}$$

WIMP MODEL

NUCLEAR MODEL

$$\sigma_{SD}^0 \propto \frac{m_{WN}^2}{m_{Wn}^2} \sigma_{SD}^{nucleón} \frac{4}{3} \frac{(J+1)}{J} \frac{1}{\bar{a}^2} \left(a_p \langle S_p \rangle + a_n \langle S_n \rangle \right)^2$$

Dark Matter Interaction Rate

$$\frac{dR}{dE_R} = \frac{\rho_0 M_{det}}{2 m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} d v^3 \left(\sigma_{SI}^0 F_{SI}^2 + \sigma_{SD}^0 F_{SD}^2 \right)$$

COHERENT INTERACTION

SPIN DEPENDENT INTERACTION

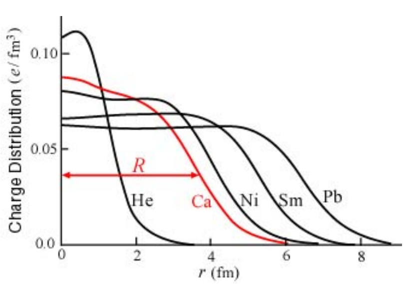
$$F(T) = \iiint e^{i\vec{p}\cdot\vec{r}} \rho(r) d^3 r$$

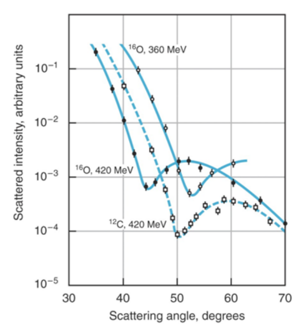
$$F(T) = 4\pi \int_0^{\infty} \sin(pr) \frac{r}{p} \rho(r) dr$$

NUCLEAR FORM FACTORS

To take into account the finite size of the nucleus and its internal structure

Loss of coherence at high momentum transfer for SI





Dark Matter Interaction Rate

$$\frac{dR}{dE_R} = \frac{\rho_0 M_{det}}{2 m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv^3 \left(\sigma_{SI}^0 F_{SI}^2 + \sigma_{SD}^0 F_{SD}^2 \right)$$

Moving into the lab frame WIMP velocity distribution is not isotropic anymore

$$\vec{v} = \vec{v}_{gal} - \vec{v}_{\oplus}$$

$$f(\vec{v}_{gal}) d^3\vec{v}_{gal} = \frac{1}{v_0^3 \pi^{3/2}} e^{-\frac{|\vec{v}_{gal}|^2}{v_0^2}} d^3\vec{v}_{gal}$$

$$\frac{dR}{dE_R} = \frac{\rho_0 M_{det}}{2 m_W m_{WN}^2} \frac{1}{v_0^3 \pi^{3/2}} \int_{v_{min}}^{v_{max}} \int_{-1}^{1} d(-\cos\theta) \int_0^{2\pi} d\varphi \frac{e^{-\frac{(\vec{v}+\vec{v}_{\oplus})^2}{v_0^2}}}{v} \sigma_{SI}^0 F_{SI}^2 \, v^2 dv$$

Dark Matter Interaction Rate

$$T(v_{min}) = \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv^3$$

$$x = \frac{v_{min}}{v_0} \qquad y = \frac{v_\odot}{v_0} \qquad z = \frac{v_{esc}}{v_0}$$

$$T(v_{min}) = \frac{1}{2v_\odot} \begin{cases} \frac{1}{N}(erf(x+y) - erf(x-y) - \frac{4}{\sqrt{\pi}} y e^{-z^2} & z - y \geq x \geq 0 \\ \frac{1}{N}(erf(z) - erf(x-y) - \frac{2}{\sqrt{\pi}}(z+y-x)e^{-z^2} & z + y \geq x \geq z - y \\ 0 & x \geq z + y \end{cases}$$

donde $N = erf(z) - \frac{2z}{\sqrt{\pi}} e^{-z^2}$ es un factor de normalización.

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt.$$

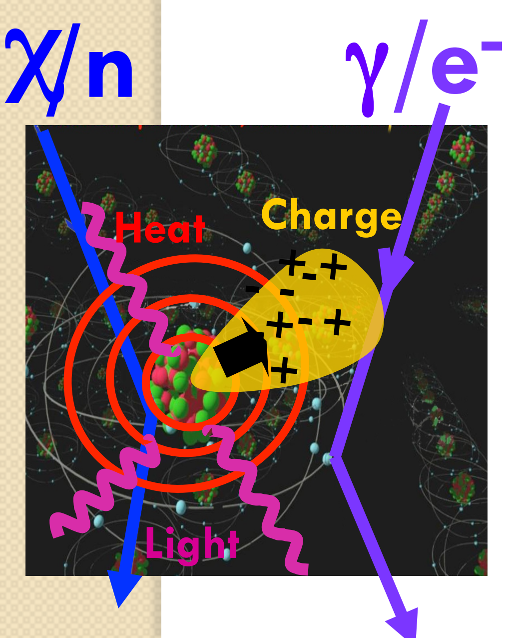
$$\frac{dR}{dE_R} = \frac{\rho_0 M_{det}}{2 m_W m_{WN}^2} \frac{1}{v_0^3 \pi^{3/2}} \int_{v_{min}}^{v_{max}} \int_{-1}^{1} d(-\cos\theta) \int_0^{2\pi} d\varphi \frac{e^{-\frac{(\vec{v}+\vec{v}_\oplus)^2}{v_0^2}}}{v} \sigma_{SI}^0 F_{SI}^2 \, v^2 dv$$

Dark Matter Interaction Rate

$$\frac{dR}{dE_{ee}} = \frac{\rho_0 M_{det}}{2Q m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv^3 \left(\sigma_{SI}^0 F_{SI}^2 + \sigma_{SD}^0 F_{SD}^2\right)$$

$$\frac{dR}{dE_R} \longleftrightarrow \frac{dR}{dE_{ee}} \qquad E_{ee} = QE_R$$

Very strong dependence on the detection technique if signal produced by nuclear recoils is very different to that corresponding to electrons used for calibration



Iodine recoils of 50 keV in NaI scintillation detector produce ~ 5 keVee

QUENCHING FACTOR

Dark Matter Interaction Rate

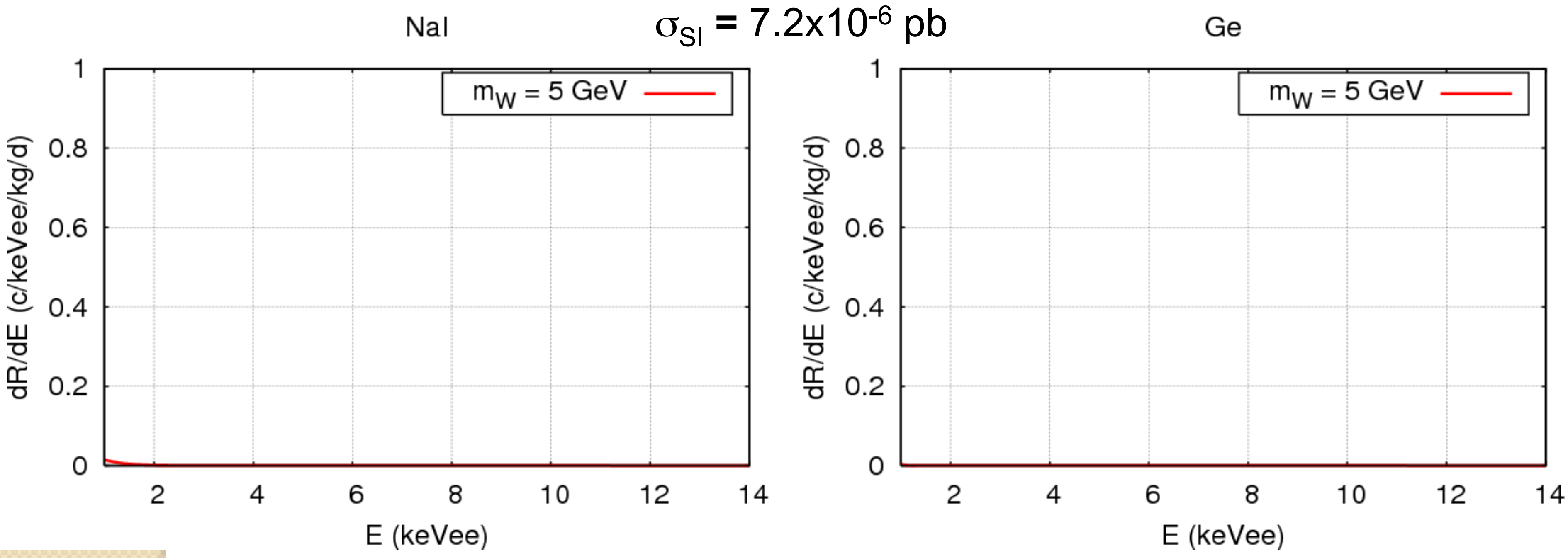
$$\frac{dR}{dE_{ee}} = \frac{\rho_0 M_{det}}{2Qm_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv^3 \left(\sigma_{SI}^0 F_{SI}^2 + \sigma_{SD}^0 F_{SD}^2\right)$$

Detector physics	Astrophysics	Particle physics
F^2 form factor m_n target nucleus mass N_T number of target nuclei E_R recoil energy **Q quenching factor**	$n_0 = \rho_0 / m_w$ local halo density f(v) WIMP velocity distr. v_{max} escape velocity	m_w WIMP mass σ_0 WIMP elastic scattering cross section
minor uncertainties	estimates	unknown

Dark Matter Interaction Rate

$$\frac{dR}{dE_{ee}} = \frac{\rho_0 M_{det}}{2Q m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv^3 \left(\sigma_{SI}^0 F_{SI}^2\right)$$

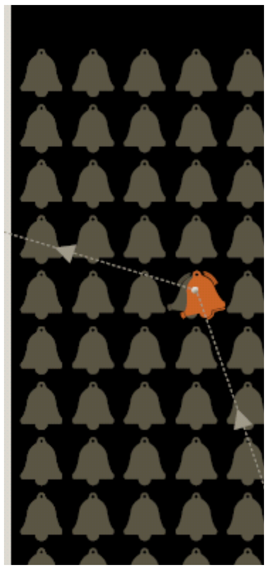
σ_{SI} = 7.2x10^{-6} pb

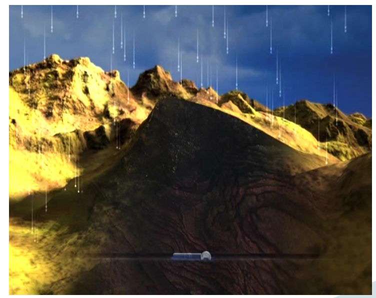


- Low energy events <20 keVee
- Very low event rates

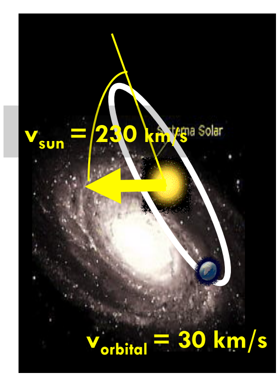
VERY LOW ENERGY THRESHOLD
VERY LOW RADIOACTIVE BACKGROUND

Strategy to face the Direct Detection of WIMPs inthe lab

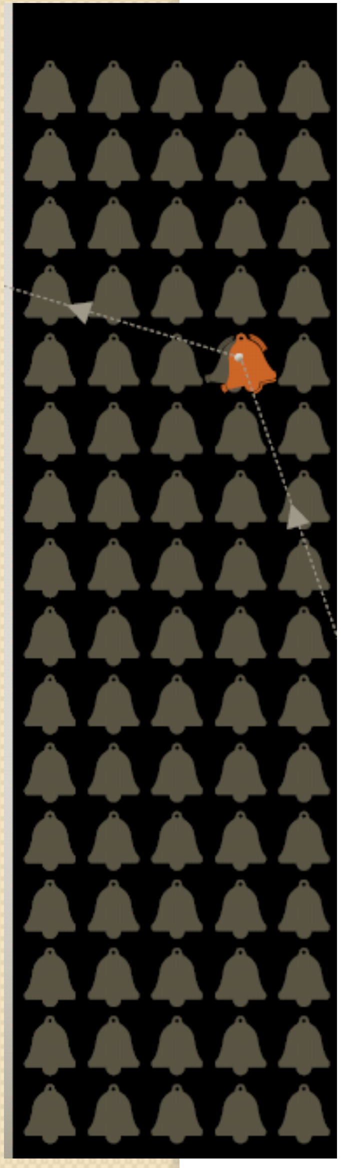




- We need very sensitive and radiopure Particle Detectors
- Experiments have to be shielded against all possible backgrounds and profit from active background rejection techniques
- Signatures of a Dark Matter interaction are required for a positive result



Particle Detection Techniques

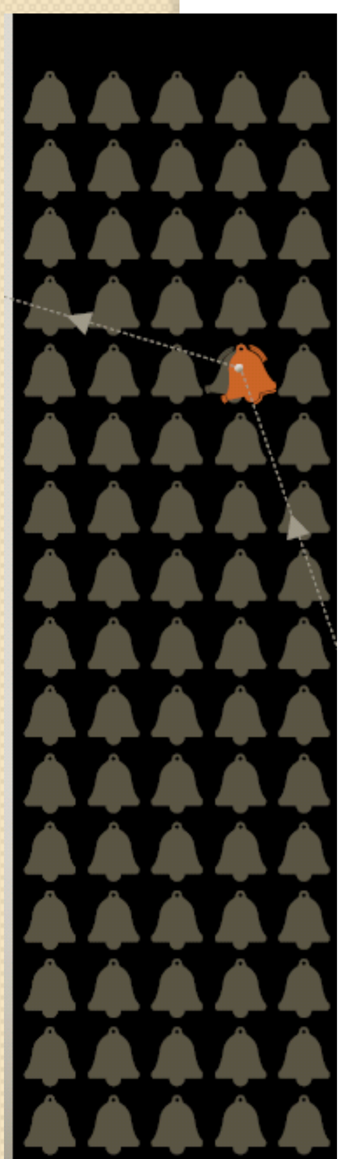


Detectors are those devices able to convert energy depositions of a particle passing through into a measurable signal

What Detectors are best suited for DARK MATTER DIRECT DETECTION?

High Radiopurity Material	Wide Absorber Choice: Light +heavy isotopes, spin content
High Mass Availability	Modularity
Low Energy Threshold	Particle Discrimination capability
High Response to Nuclear Recoils	Low Price
Stability	State of the art

Particle Detection Techniques



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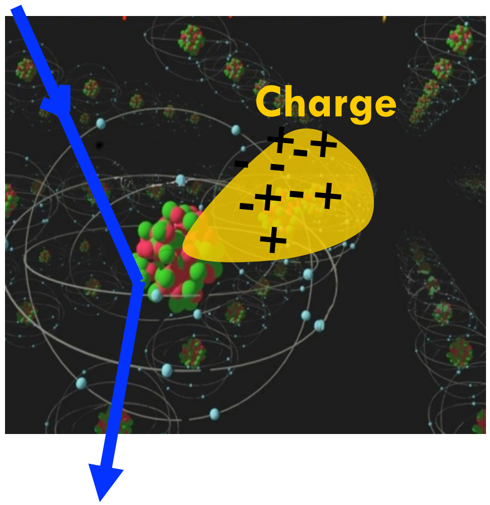
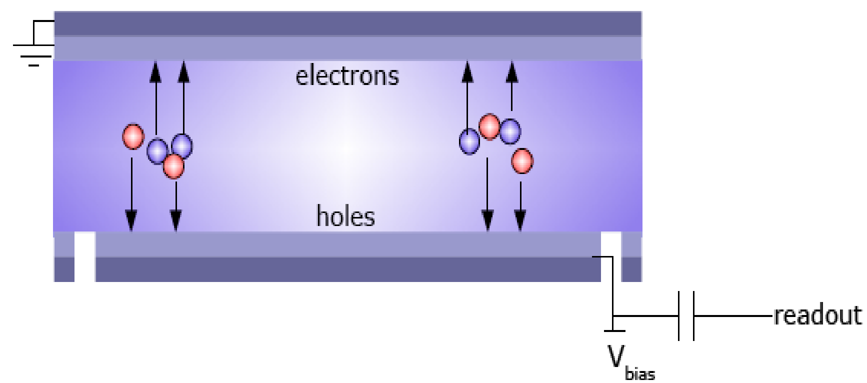
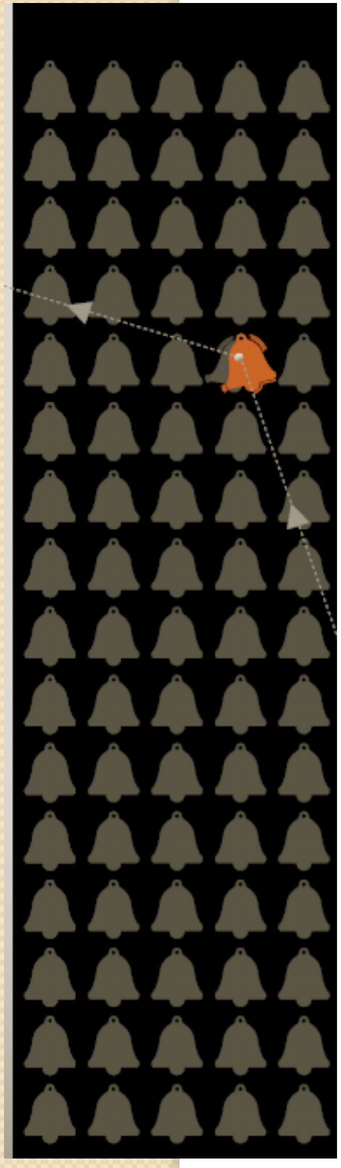


IONIZATION Detectors collect the charge carriers produced by a particle interaction



Ge detectors showed good threshold and resolution low intrinsic radioactivity: first DM direct searches back in the eighties

Particle Detection Techniques



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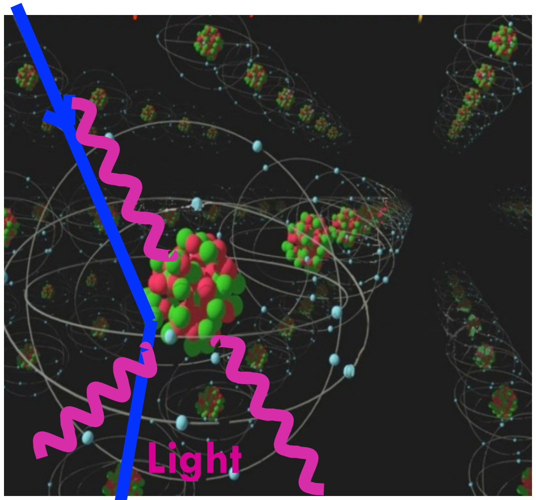
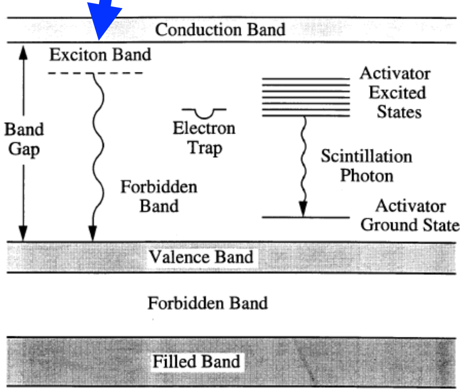




SCINTILLATION Detectors collect the light produced by a particle interaction

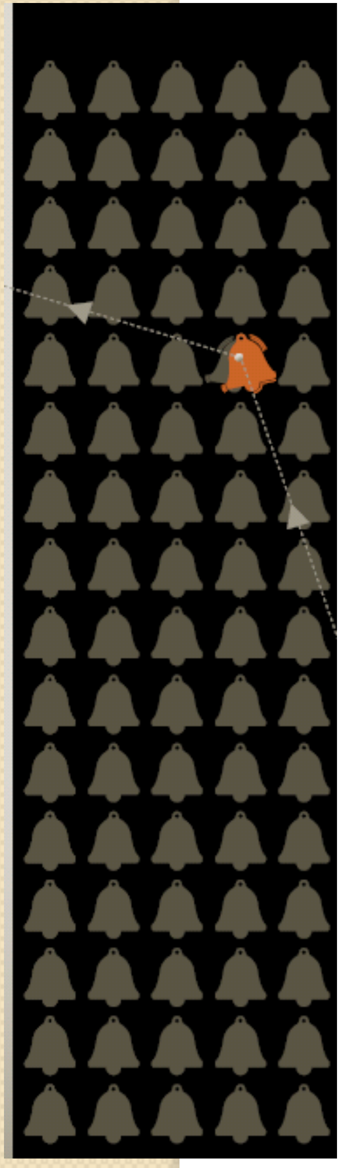
Solid State Scintillators have applied in this field: NaI CsI

Noble liquids based experiments: Xe Ar Ne

Both allow high mass experiments

But scintillation less effective in energy conversion (quenching!!!)

Particle Detection Techniques



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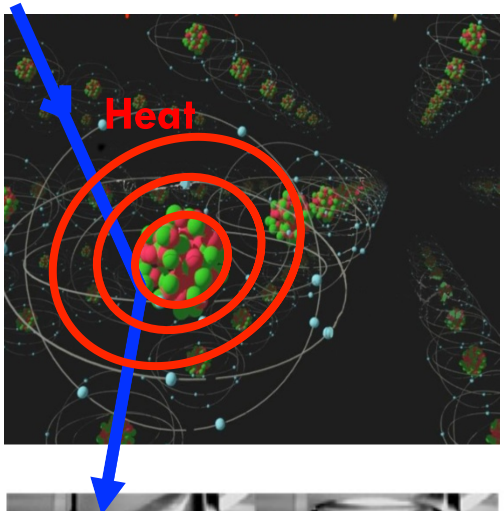
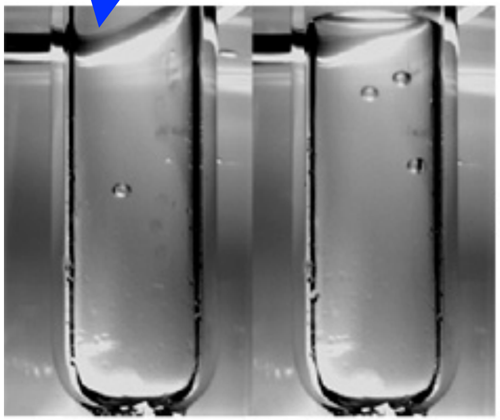


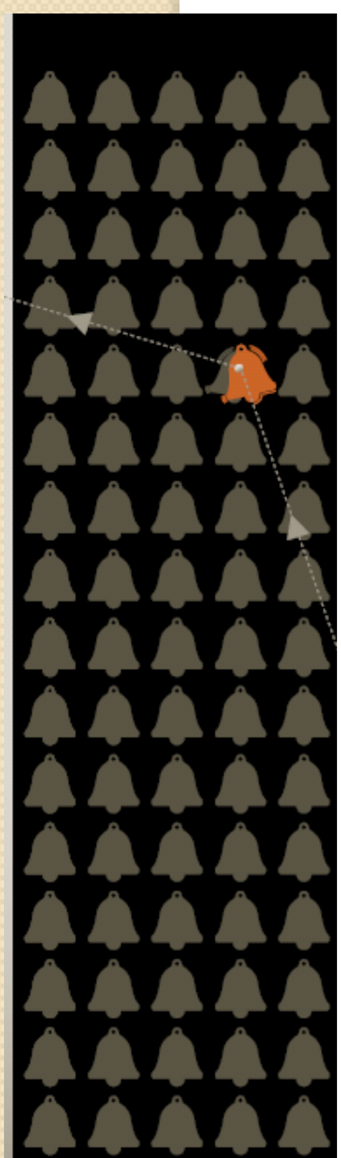


Bubble chambers consist of superheated liquids where heat released by a particle interaction is able to produce the nucleation of a vapor phase

Very sensitive to high stopping power particles

Threshold detector (does not measure released energy)

Particle Detection Techniques



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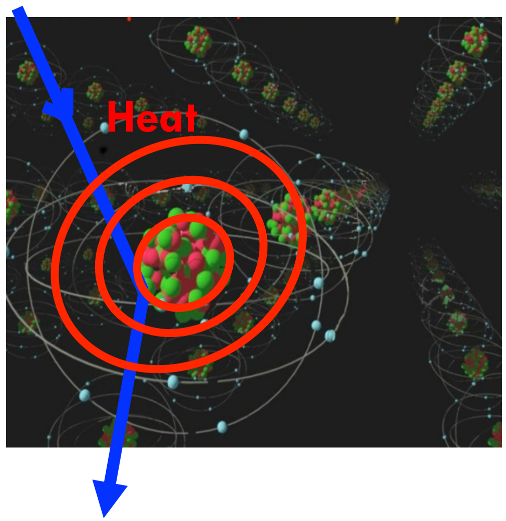
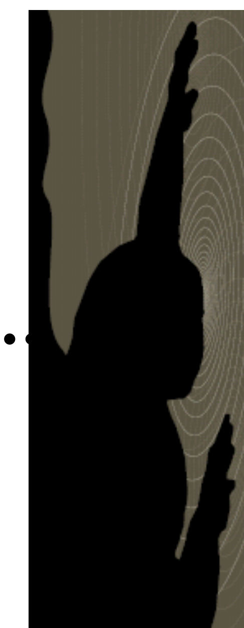
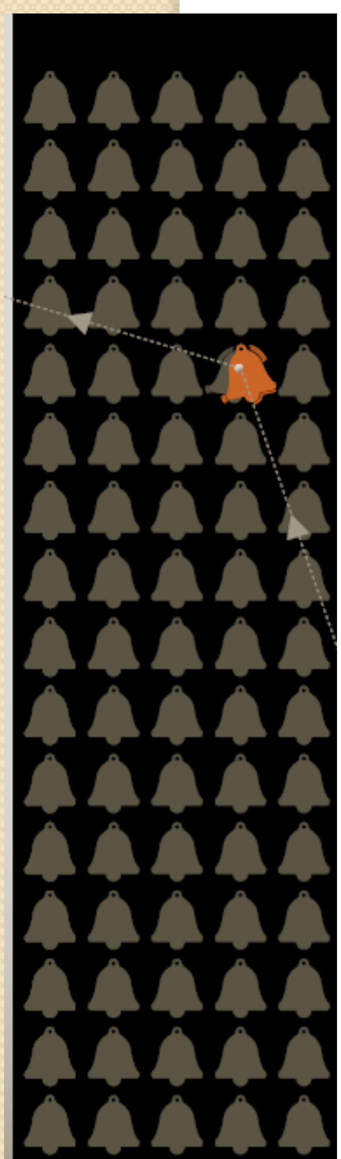


THERMAL Detectors are directly sensitive to the heat (phonons lattice vibrations produced by a particle interaction)



Wide absorber choice Ge, Al_2O_3, BGO, $CaWO_4$, ..
Very sensitive to nuclear recoils ($q \approx 1$)
Low threshold energy
Good particle discrimination capability

Particle Detection Techniques



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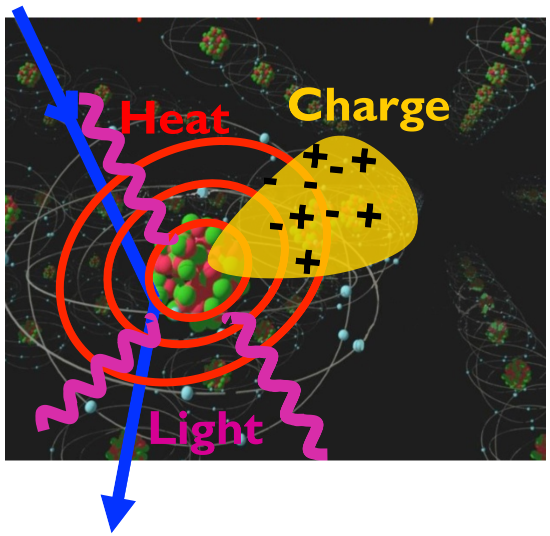
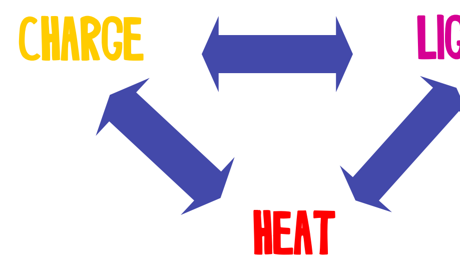


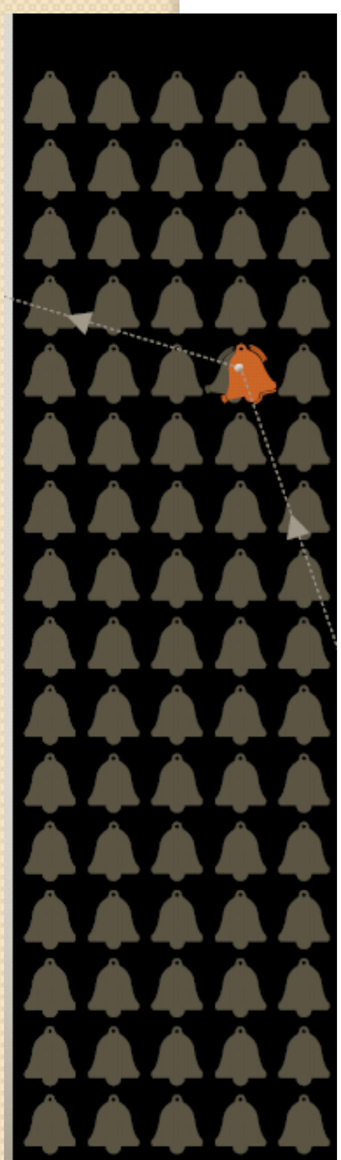
HYBRID Detectors profit from the simultaneous measure of two energy conversion channels



Energy conversion into VISIBLE signal is strongly dependent on the interaction mechanism incident particle and target allowing for PARTICLE DISCRIMINATION

THE MOST SENSITIVE TECHNIQUES AT PRESENT

Particle Detection Techniques



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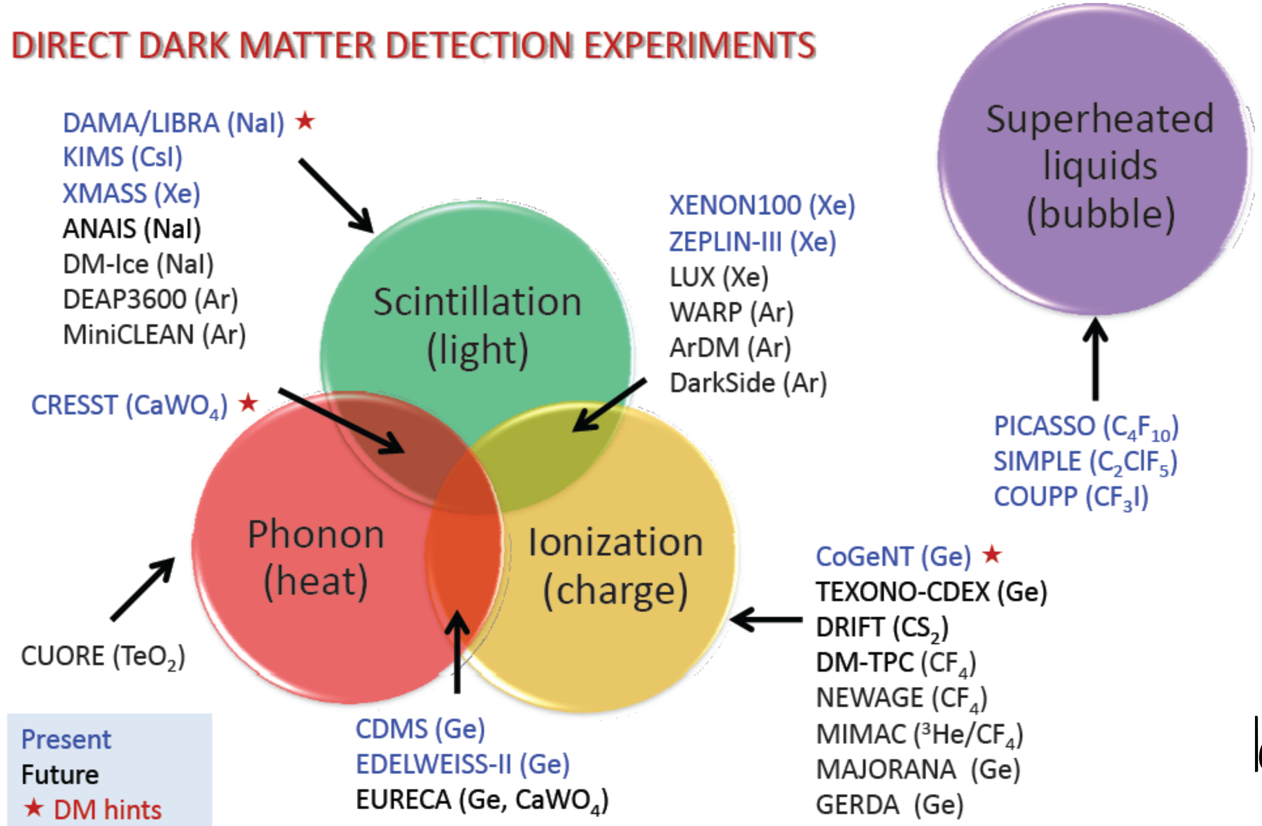

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Detectors are those devices able to convert energy
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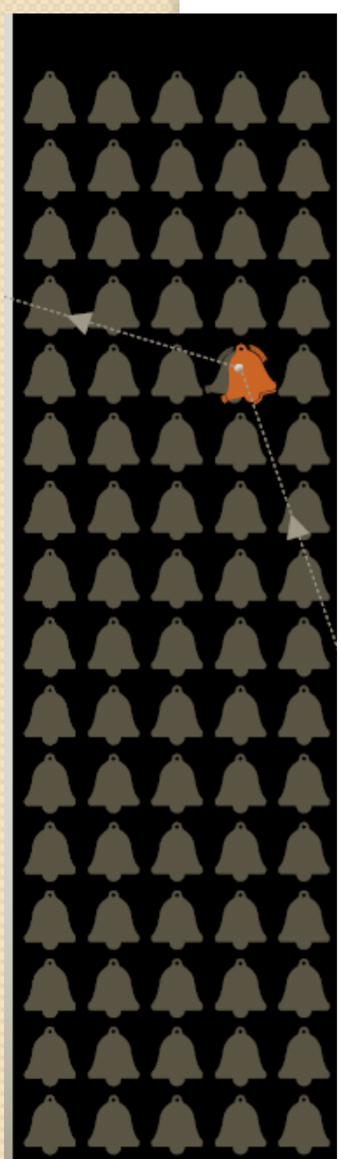

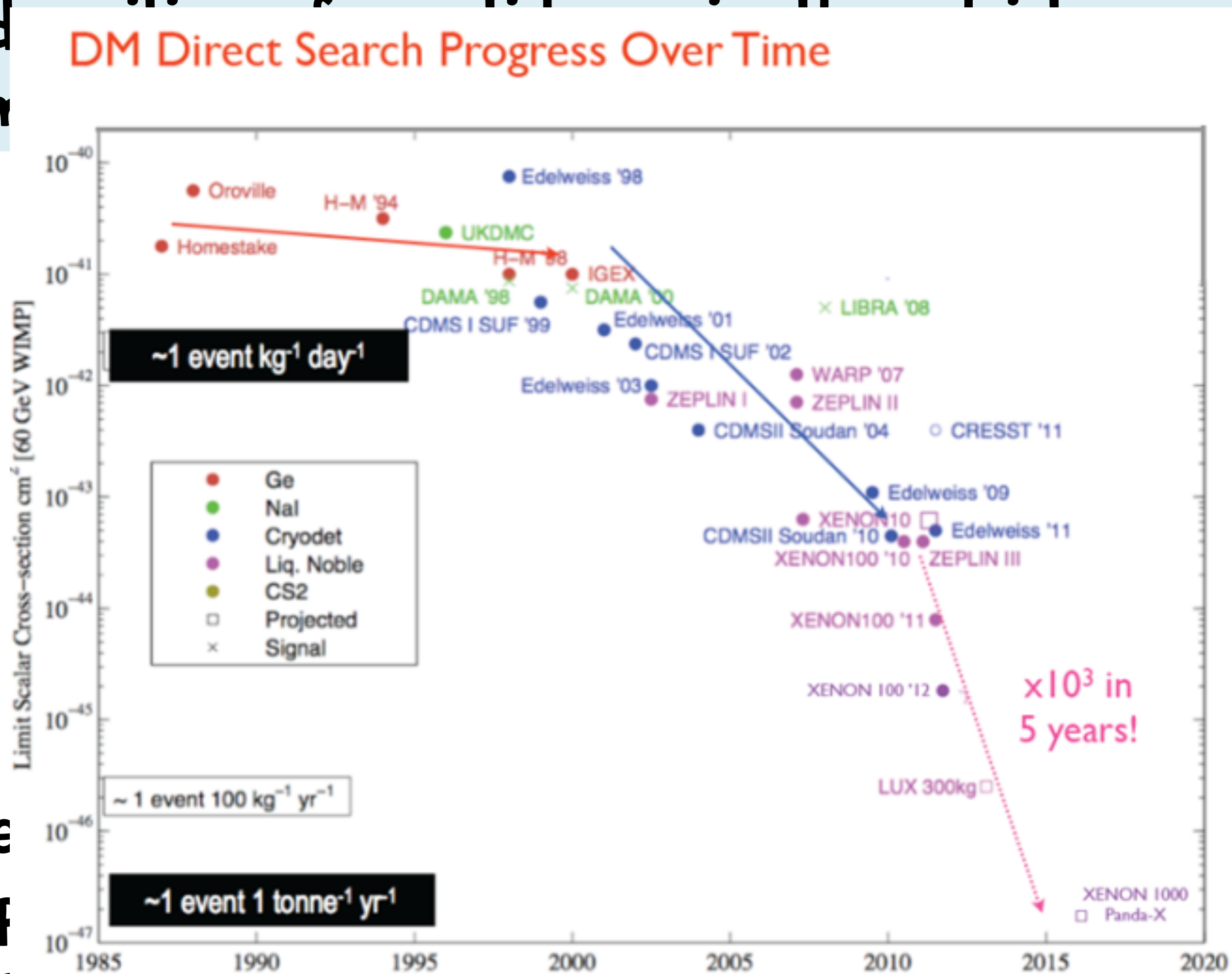

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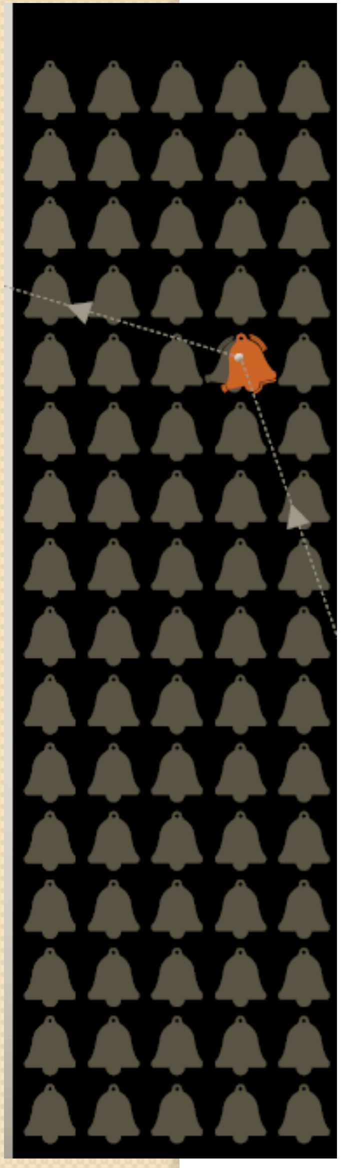
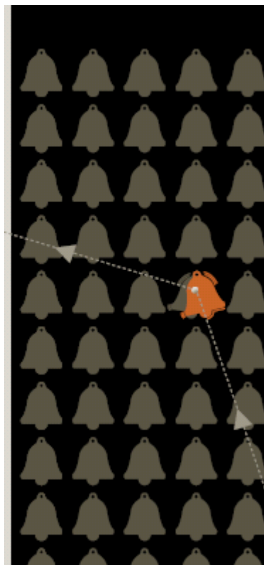
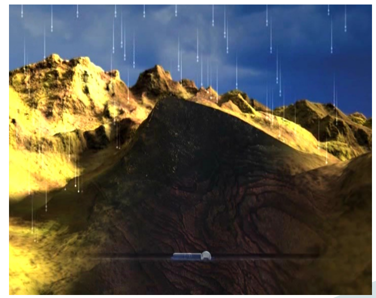


NEW DETECTORS
DNA based dark matter detectors

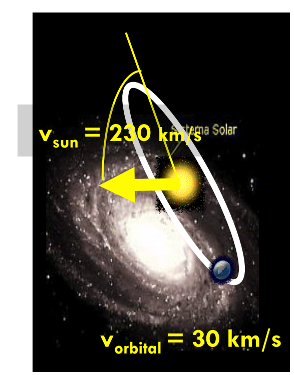
REVISITED OLD DETECTORS
Nuclear emulsions

Strategy to face the Direct Detection of WIMPs inthe lab





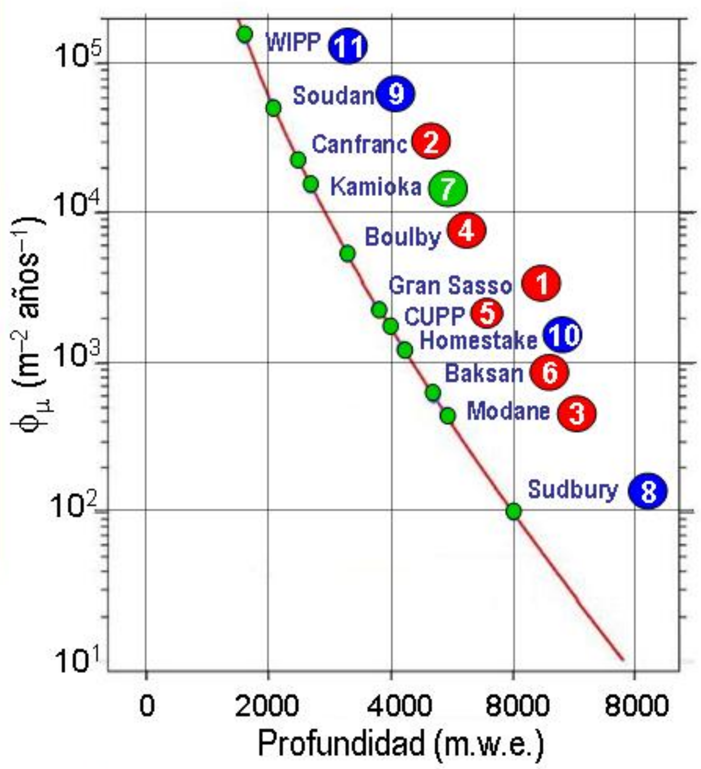
- We need very sensitive and radiopure Particle Detectors
- Experiments have to be shielded against all possible backgrounds and profit from active background rejection techniques
- Signatures of a Dark Matter interaction are required for a positive result

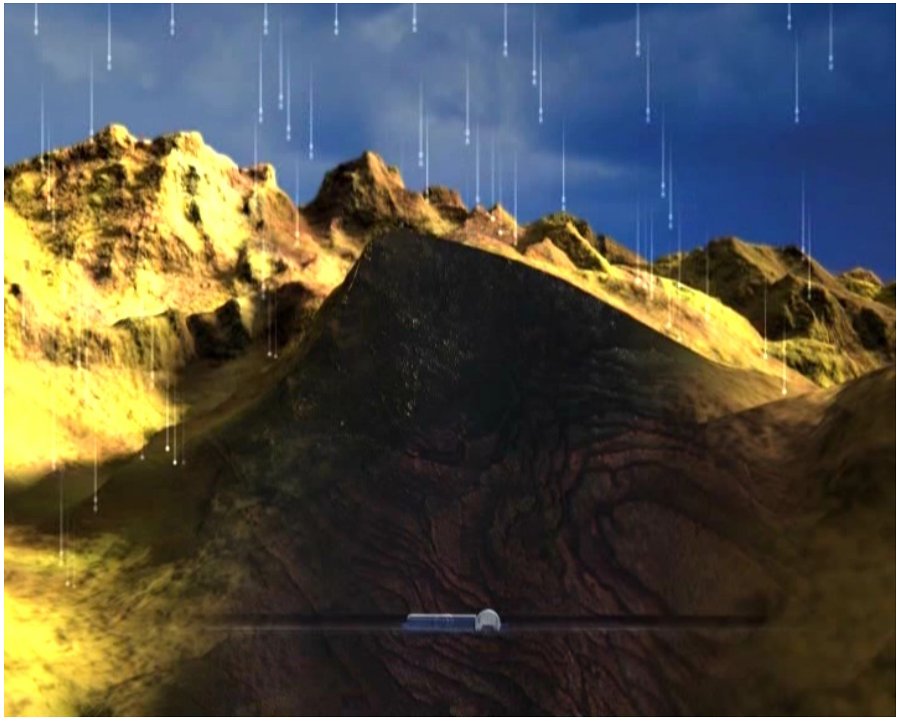


Shielding Strategies

Background signals interferring with WIMP detection come from

-COSMIC Rays
-Environmental Radioactivity





Underground Laboratories

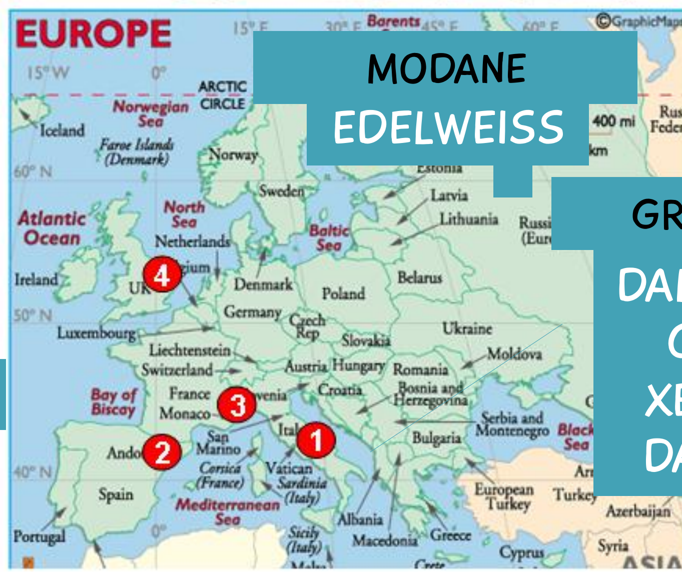
SNO
PICASSO
COUPP
SUPERCDMS
DEAP/CLEAN

SOUDAN
CDMS
CoGeNT

SANFORD
LUX
LZ

BOULBY
ZEPLIN
DRIFT

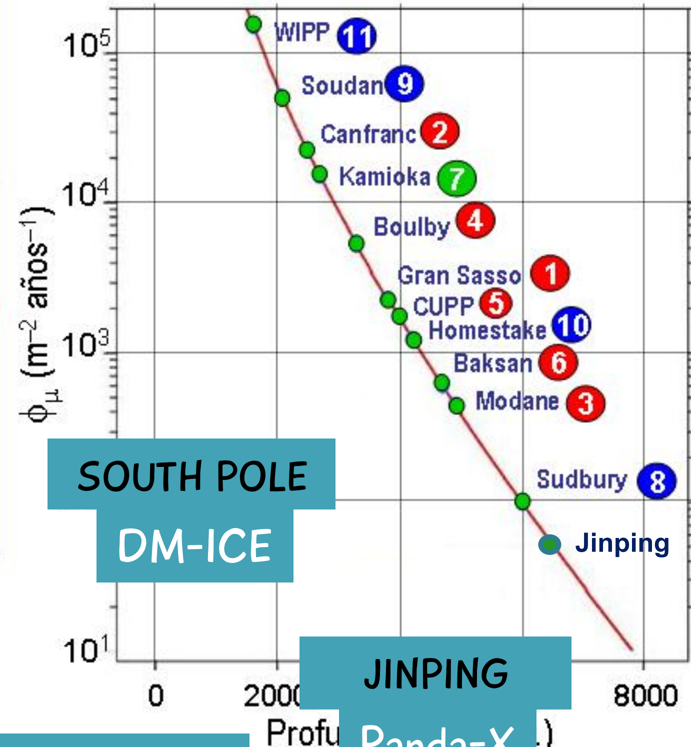
CANFRANC
ANAIS
ArDM



MODANE
EDELWEISS

GRAN SASSO
DAMA/LIBRA
CRESST
XENON100
DARKSIDE

SOUTH POLE
DM-ICE

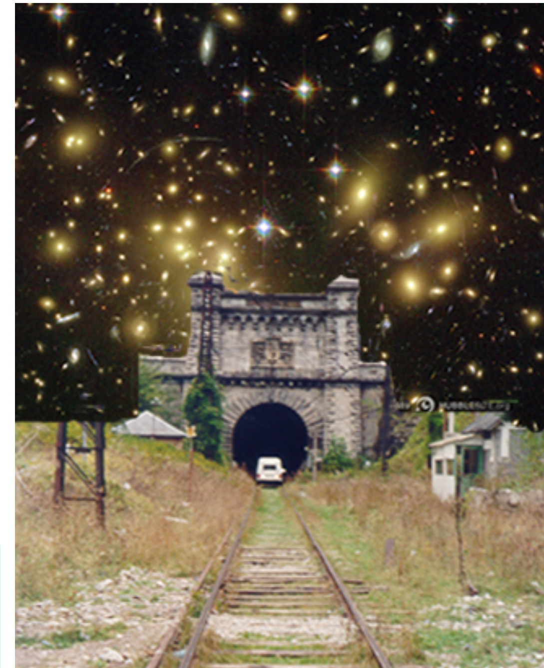


JINPING
Panda-X
CDEX

KAMIOKA
Xmass
NewAge

YANGYANG
KIMS

The Canfranc Underground Laboratory

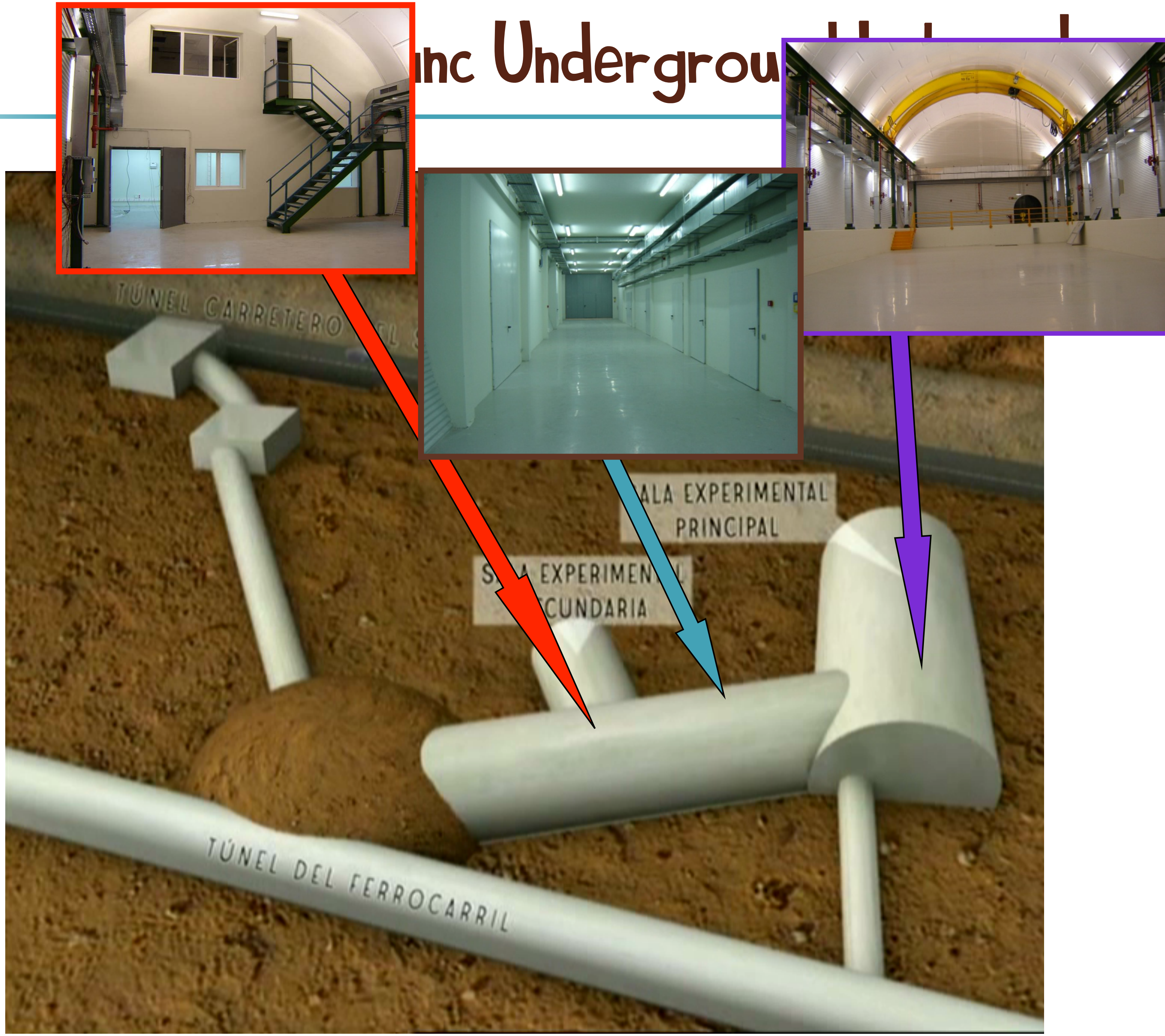


Since 1985 an underground laboratory under the Pyrenees

2450 m.w.e. rock overburden

Somport railway tunnel

nc Undergrou



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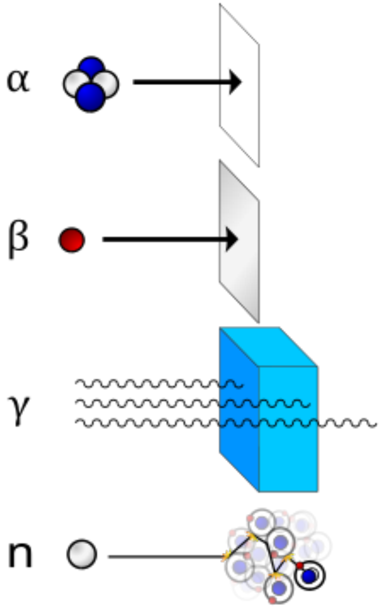
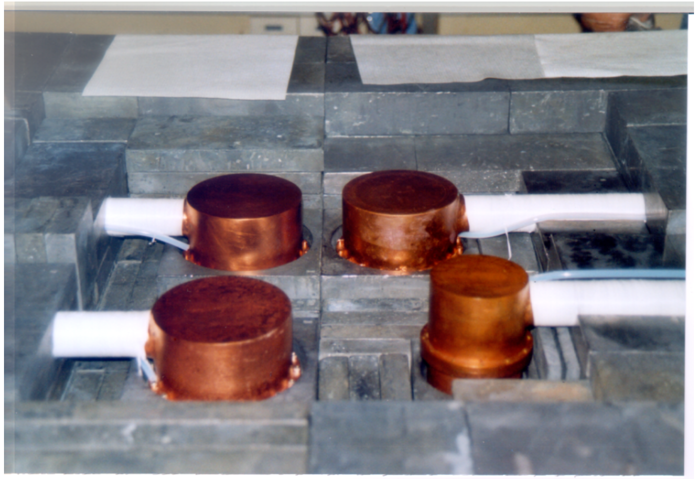
Convenient shieldings against:
Gammas, Neutrons, Muons, Radon





Environmental Radioactivity

More than 60 radioactive isotopes in the environment

60 decays/s/kg

Núclido	Símbolo	Vida media	Actividad natural
Uranio 235	235U	7.04 x 10^8 yr	0.72% del Uranio natural
Uranio 238	238U	4.47 x 10^9 yr	99.2745% del Uranio natural (0.5 a 4.7 ppm total uranio en rocas comunes)
Torio 232	232Th	1.41 x 10^{10} yr	1.6 a 20 ppm en rocas comunes
Radio 226	226Ra	1.60 x 10^3 yr	16 Bq/kg en arcillas y 48 Bq/kg en roca ígnea
Radon 222	222Rn	3.82 days	Gas noble; promedio anual en aire 0.6 Bq/m^3 a 28 Bq/m^3
Potasio 40	40K	1.28 x 10^9 yr	0.037-1.1 Bq/g
Tritio	3H	12.3 yr	Tests armas nucleares y reactores de fisión
Yodo 131	131I	8.04 days	Producto de fisión y utilizado en el tratamiento de problemas de tiroides
Yodo 129	129I	1.57 x 10^7 yr	Producto de fisión
Cesio 137	137Cs	30.17 yr	Producto de fisión
Estroncio 90	90Sr	28.78 yr	Producto de fisión
Tecnecio 99	99Tc	2.11 x 10^5 yr	Producto de desintegración del 99Mo, utilizado en diagnosis médica
Plutonio 239	239Pu	2.41 x 10^4 yr	238U + n--> 239U--> 239Np +ß--> 239Pu+ß

WIMP << 1 interaction / kg/day

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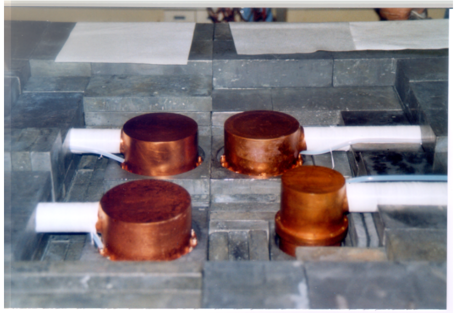

Active Background Rejection:

-Nuclear vs. Electron Recoils

-Multiple Scattering/ Combination of different targets

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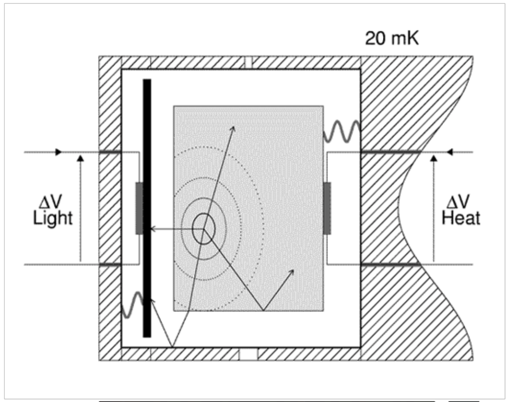

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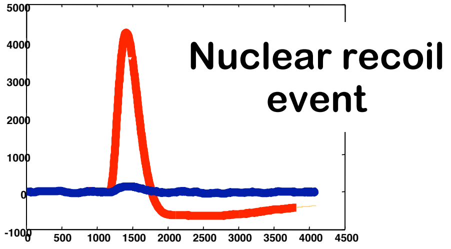

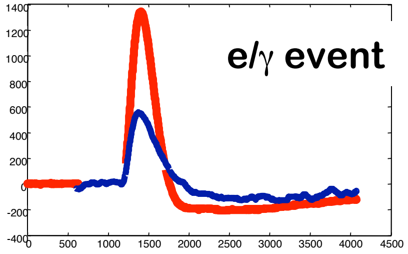

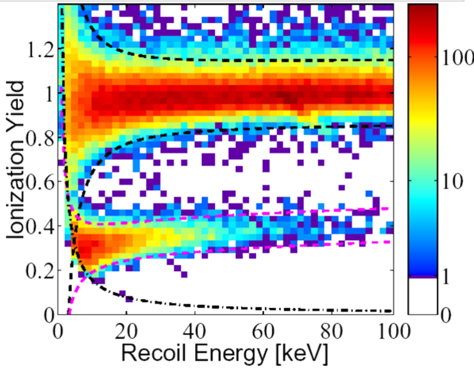

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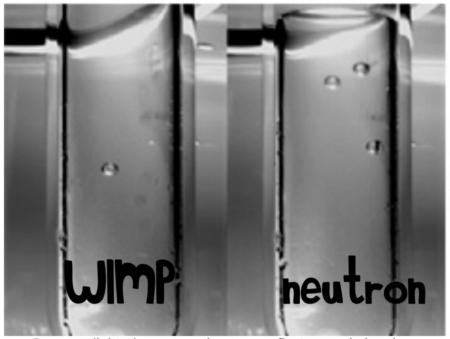

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