XIV.

The quest for Dark Matter in the Microcosm and Macrocosm

Astroparticle Physics a.a. 2021/22

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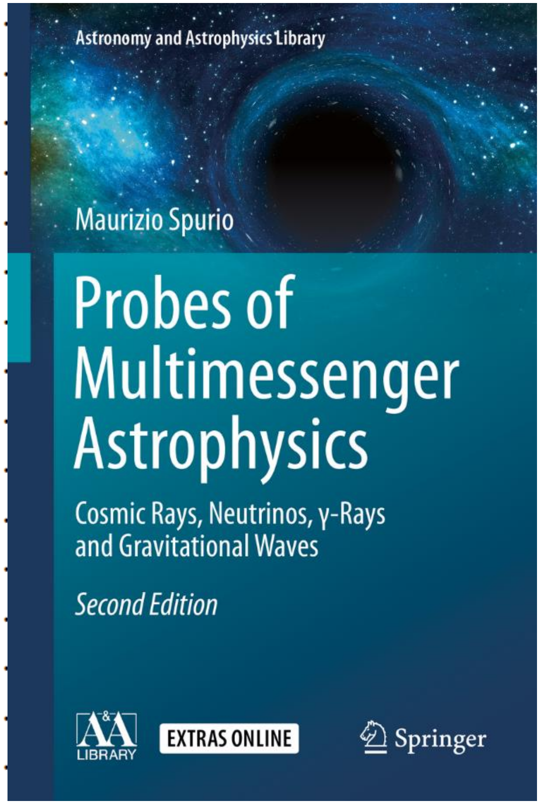
Content



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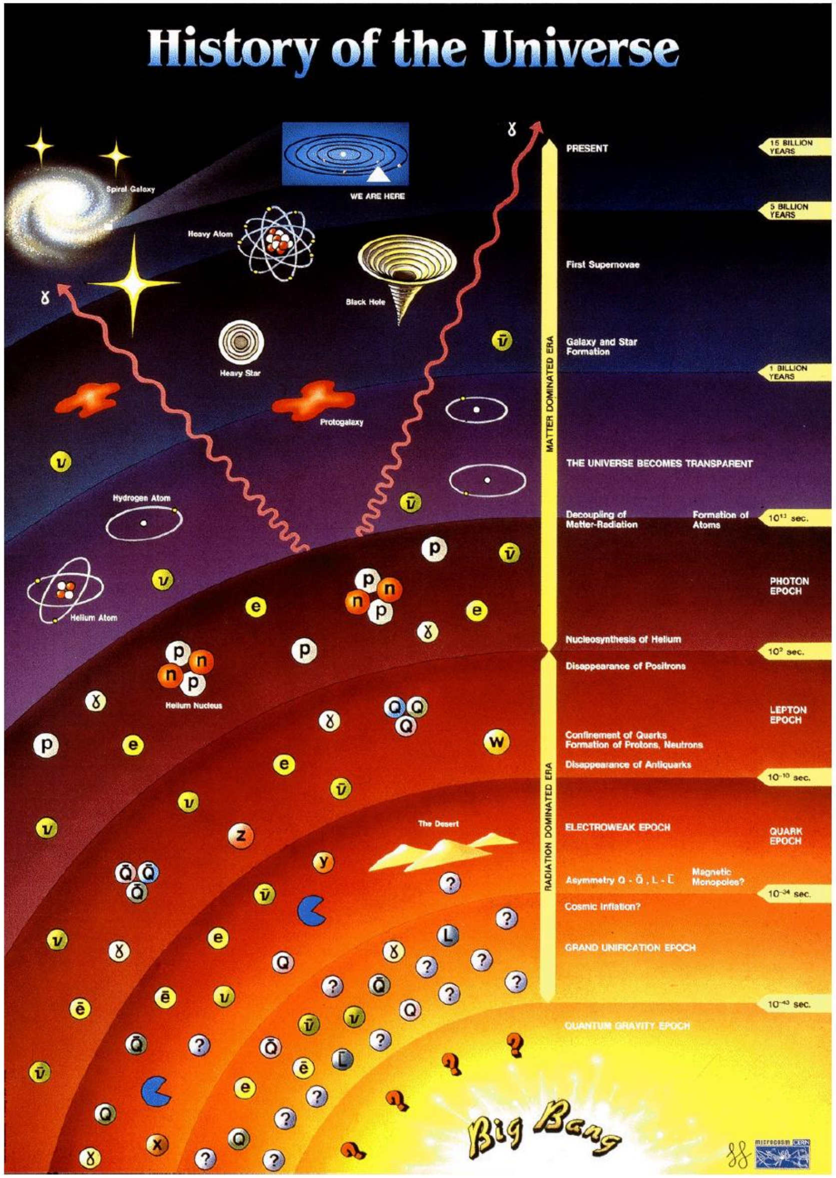
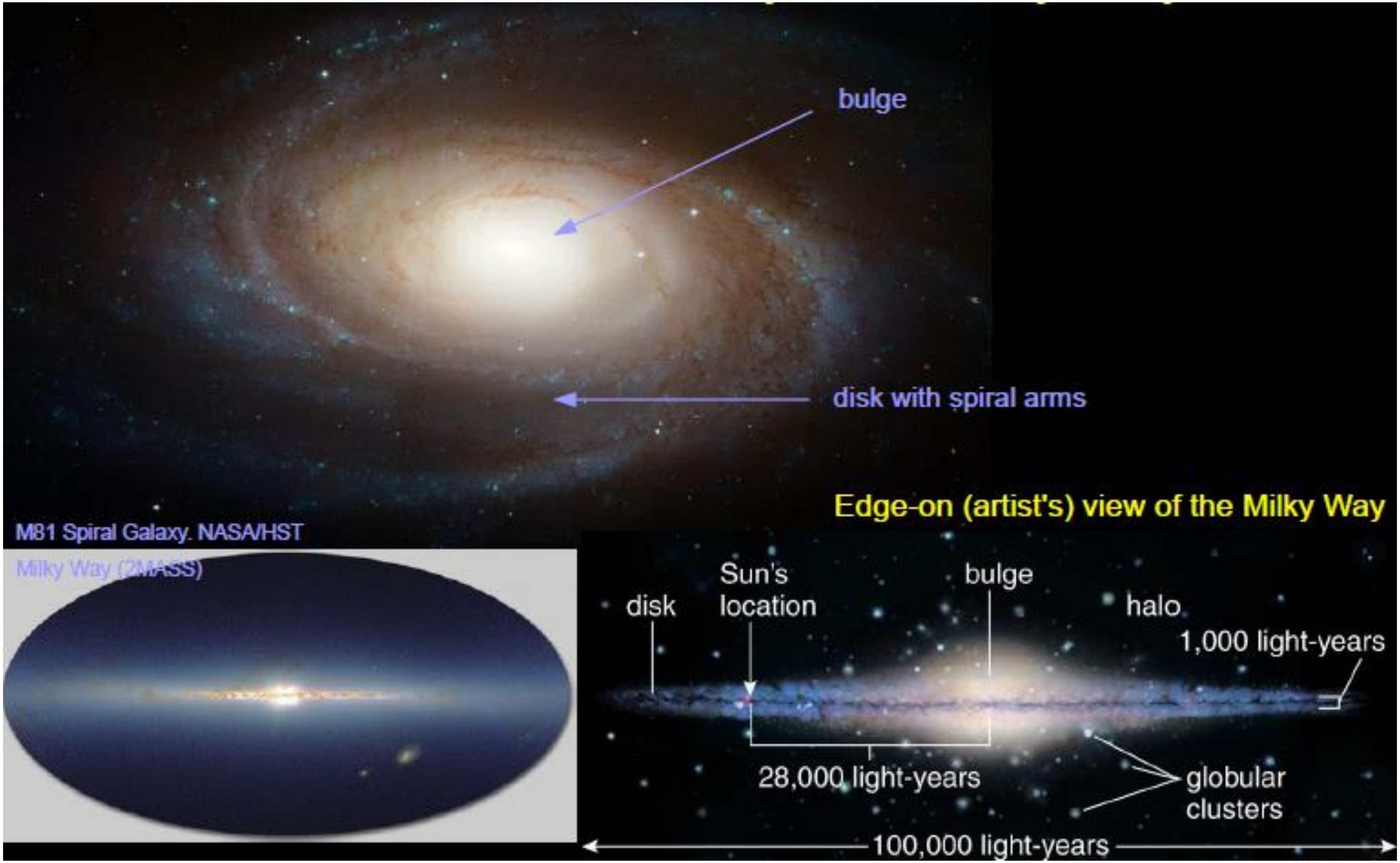
Thermal history of the Universe

- There are important connections between astrophysics, particle physics, cosmology;
- The Universe is expanding: the energy per particle decreases, phase transitions took place, the nature of particles changed, and there was a symmetry breaking from unified to non-unified interactions
- **Observational cosmology** indicates that the geometry of the Universe is flat, with density $\rho_c = 8.5\times10^{-27}$ kg/m^3 =**5 protons/m^3**
- The largest fraction (~70 %) of the mass-energy is an unknown form of **dark energy**;
- about 25) of the mass-energy is made of an unknown form of **dark matter**;
- Only ~5 % is in term of **baryonic matter**
- the matter–antimatter asymmetry observed in the Universe is not justified by the charge-parity violation allowed within the SM.

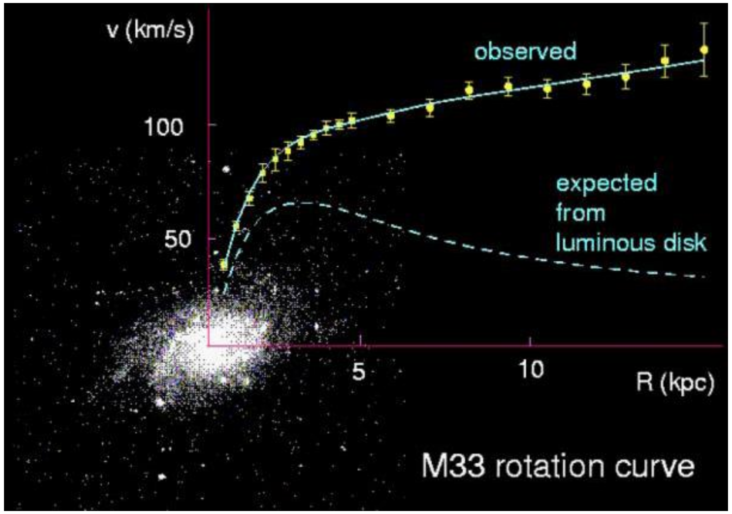


Structure of the MilkyWay



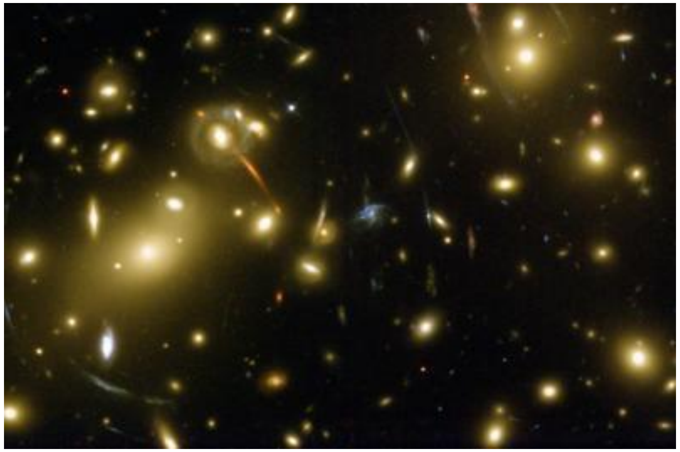
Astronomical evidences for Dark Matter

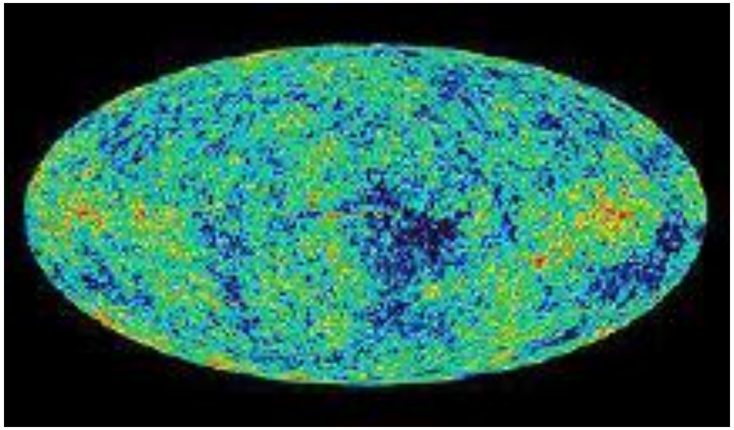
- 1933: Zwicky realized that the mass of the luminous matter in the Coma cluster was much smaller than its total mass implied by the motion of cluster member galaxies-
- Today, evidences at different scales



Rotation curves of stars in galaxies

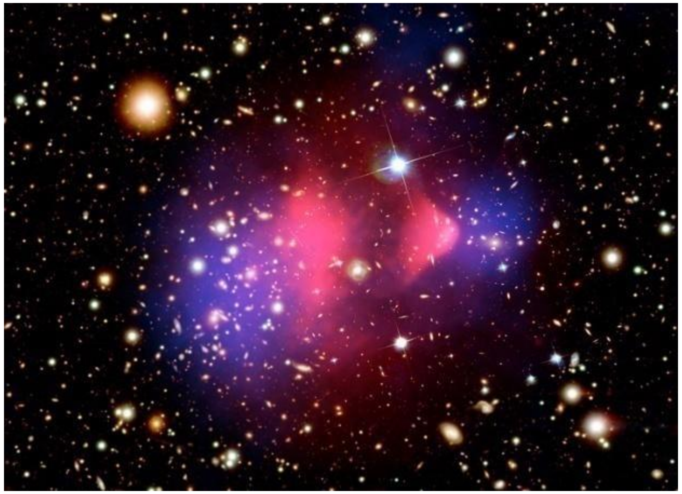
Gravitational lensing





Structure formation, as deduced from CMB

Bullet cluster



Rotation speed of stars in galaxies

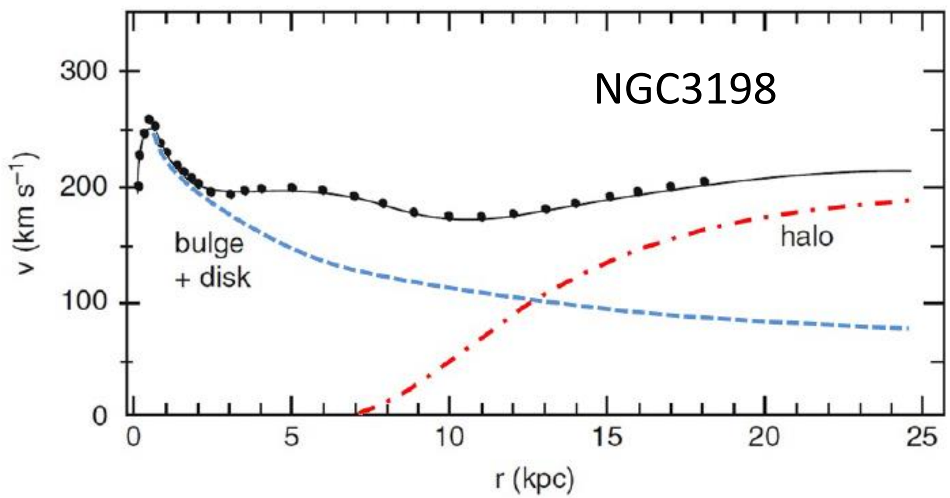
- A robust evidence for DM emerges from the analysis of the revolution speeds of stars and gas clouds in the galactic halo as a function of the distance from the center.
- The revolution speed of a mass *m* star around the center of a galaxy is determined by:

$$(14.4) \quad \frac{G_N m M_r}{r^2} = \frac{m v^2}{r} , \quad \rightarrow \quad v(r) = \sqrt{\frac{G_N M_r}{r}} . \quad (14.5)$$

- The data are obtained measuring the star speed through the Doppler effect
- Most of the stars of a spiral galaxy are located in the central bulge with radius r_s and thus the expected speeds are:

$$(14.6a) \quad v(r) = \sqrt{\frac{4}{3}\pi G_N \overline{\rho}} \cdot r \propto r \quad \text{for } r < r_s .$$

$$(14.6b) \quad v(r) \propto 1/\sqrt{r} \quad \text{for } r > r_s .$$



Speed of stars vs. r in NGC3198. Dashed line: expected contribution based on the visible matter (bulge+galactic disk); dotted dashed line: includes the hypothetical halo of DM.

Clusters of galaxies=gas + galaxies + ?

- Clusters of galaxies are composed of **galaxies**, **hot gas** and (?) **dark matter**
- The mass of the galaxies can be estimated through their EM luminosity
- The mass of the hot gas by their X-ray emission
- The diffuse **hot gas** has a mass larger than the masses of **galaxies**.
- Only **3%** of the mass in clusters of galaxies is due to **stars in galaxies**, and about **15%** is contributed by the **intergalactic gas**, whereas the remaining **80%** should consist of **dark matter** which therefore dominates the mass of the clusters.

- *In white, on optical image of the Coma cluster.*
- *Superposed is the X-ray emission (pink) which highlight the filamentary structure of the hot gas.*
- *These filaments are most likely due to a past merger events, when smaller groups fall into the main cluster; their gas was stripped by ram-pressure during infall, leaving trails of gas.*
- *The sidelength of the image is about 600 kpc.*

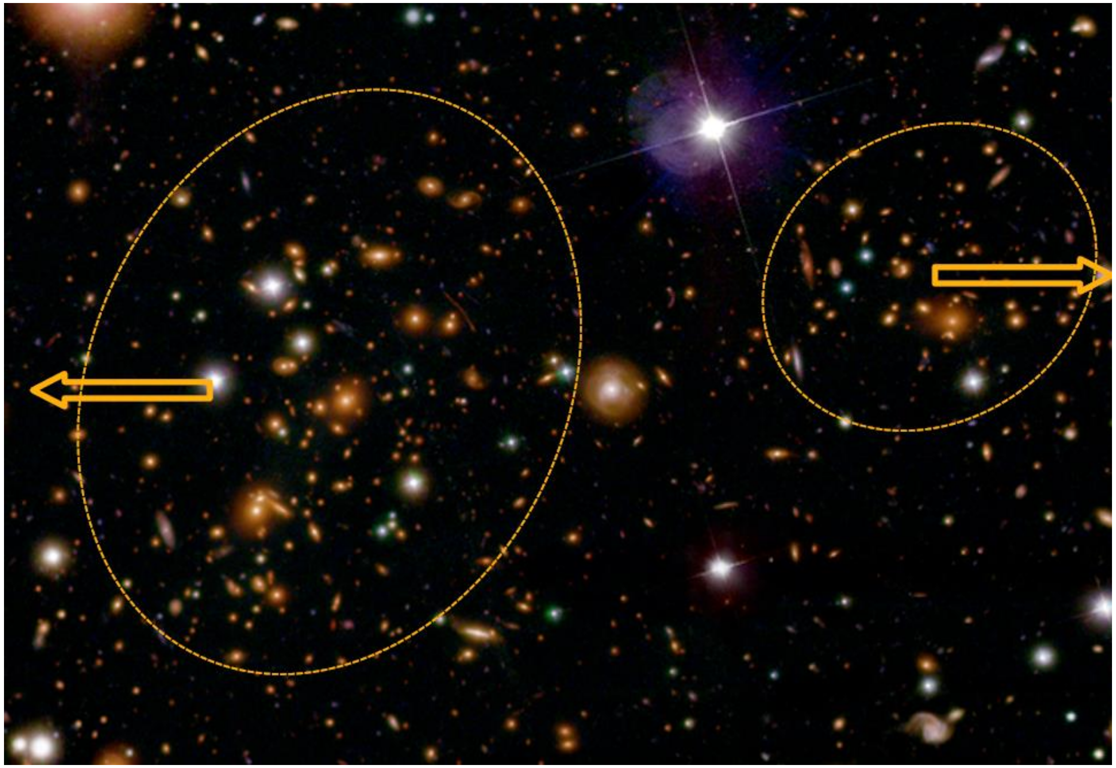
Credit: X-ray: NASA/CXC/MPE/J. Sanders et al., Optical: SDSS

A particular cluster: the *bullet cluster*

- One of the most striking evidence for the presence of DM on the length scales of galaxy clusters comes from the observations of a pair of colliding clusters
- The **`bullet cluster'** is located 3.7 Gyr away, with a catalog name 1E0657-558. The two objects "*collided*" 150 million years ago.
- **Galaxies behave like a non-collisional fluid**. A collision between two clusters would hardly alter their motion and spatial distribution.
- **Gas particles are a collisional fluid**. A collision would strongly alter their motion and spatial distribution.
- If present, **dark matter would have a non-collisional nature** and would dominate the mass of the cluster.
- A collision between two clusters should therefore separate the two different "phases" of the clusters. The non-collisional one (**galaxies** and, if exists, **dark matter**) would be slightly perturbed. The collisional one (**the gas**) would instead be strongly perturbed, slowing down with respect to the stellar component.
- The total mass of a cluster can be also estimated by **gravitational *lensing*** *methods (*an important astronomical tool, not described in this cours)

Bullett cluster – visible image

- The visible image shows two distinct groups of galaxies separated by about 700 kpc and moving away with a relative speed of about 4500 Km s^{-1}.
- The shape of the two structures is quite regular, confirming the fact that galaxies behave like a non-collisional fluid.

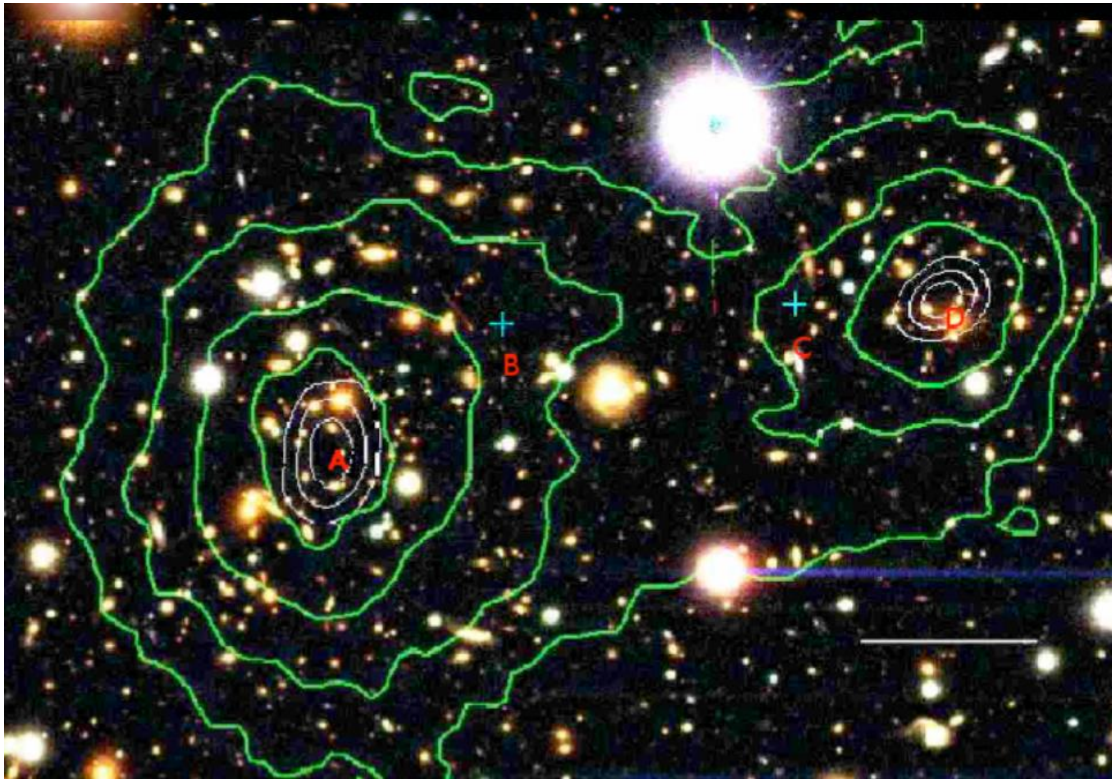


Bullett cluster – X-ray

- When observed in the X band (superimposed on the optical one) two bright areas can be seen corresponding to the regions in which the gas is densest
- These regions do not coincide with the concentrations of galaxies and have distorted shapes. In the one on the right there is a shock front, similar to that produced by the passage of a bullet. The collisional nature of the gas is confirmed.

Bullett cluster – Gravitational lensing

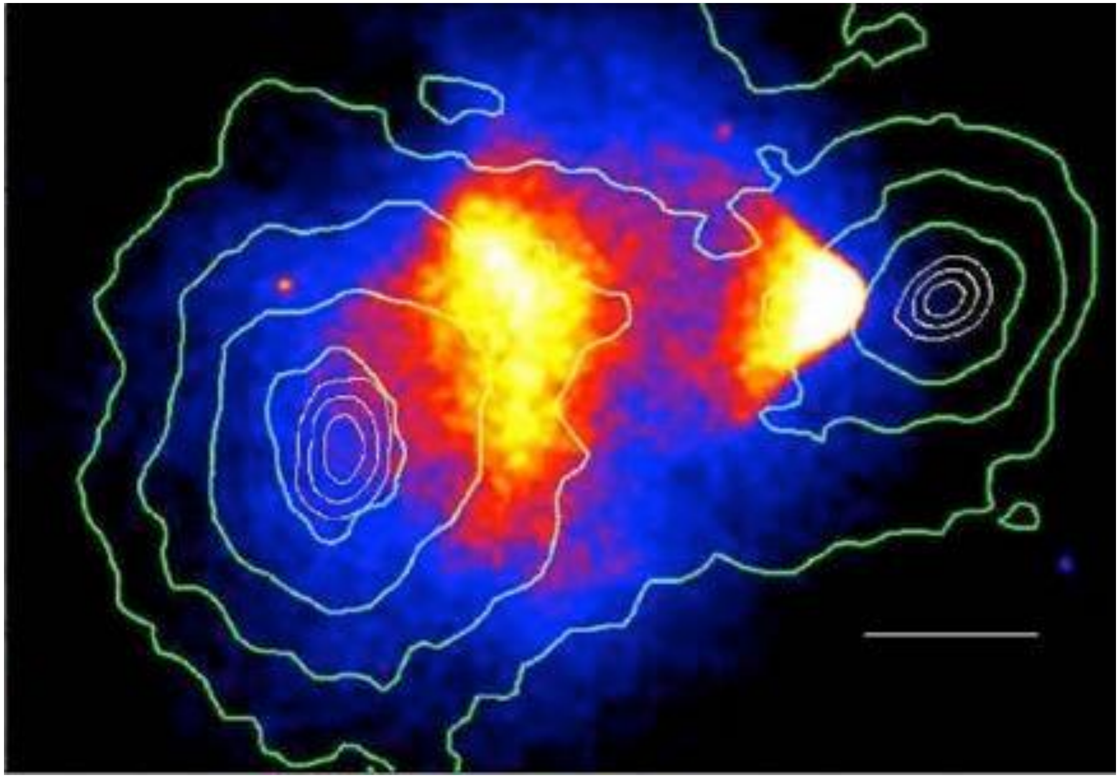
- The phenomenon of gravitational lensing allows to trace the spatial distribution of the total mass in a cluster. Observing the lensing effect in the Bullet Cluster allows us to trace the contours of isodensity in the figure (in green).
- The distribution of the total mass coincides with the position of galaxies. This indicates that the largest fraction of the mass is non-collisional, and **due to the DM** .



Bullett cluster – Dark Matter

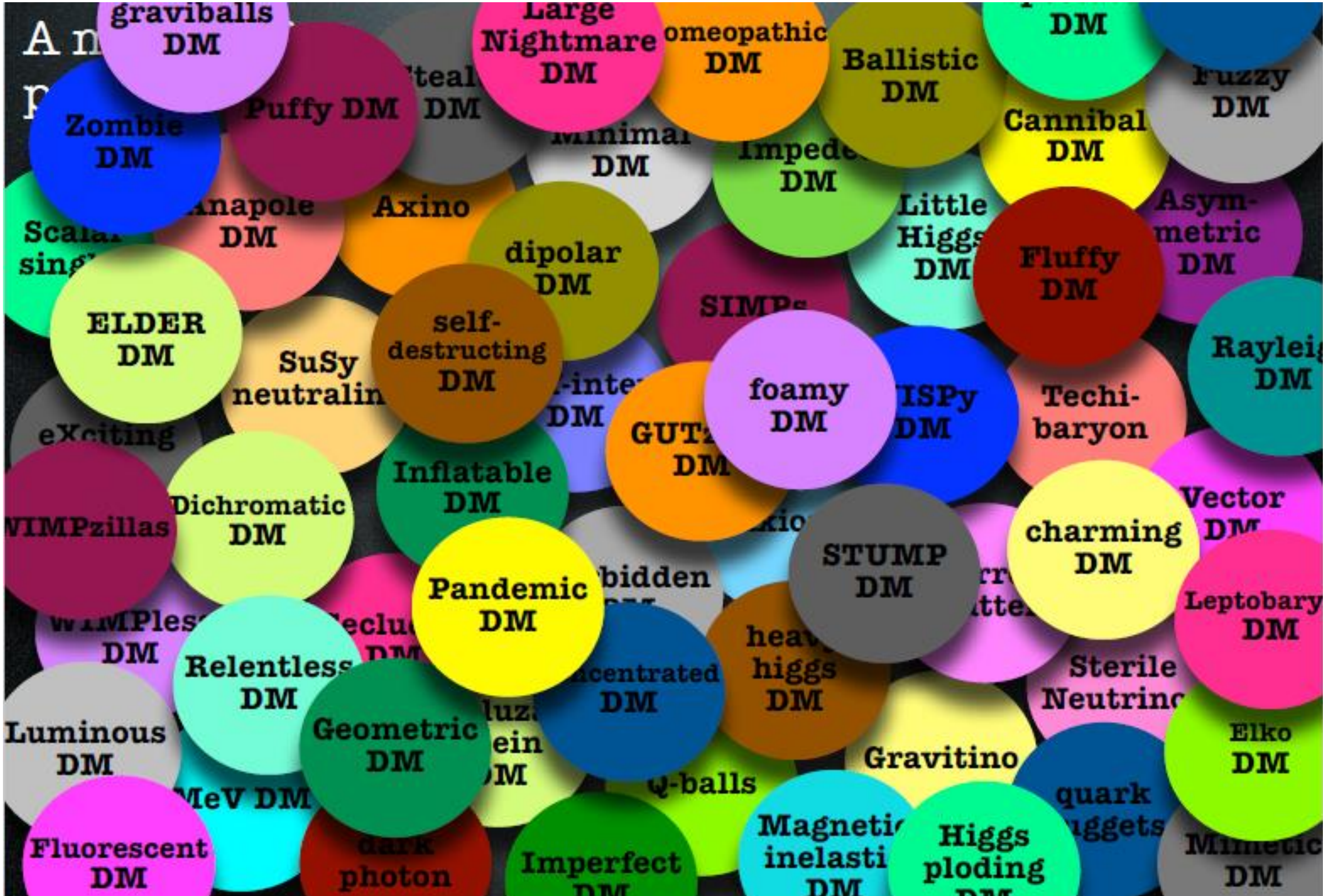
The gas distribution is decentralized than to that of the total mass. We conclud:

1. The mass fraction of the gas is minority (not corresponding to green lines maxima)
2. Most of the mass is distributed like galaxies and therefore is non-collisional
3. The mass of the cluster is dominated by a dark component.



Theoretical candidates (until 5 years ago)

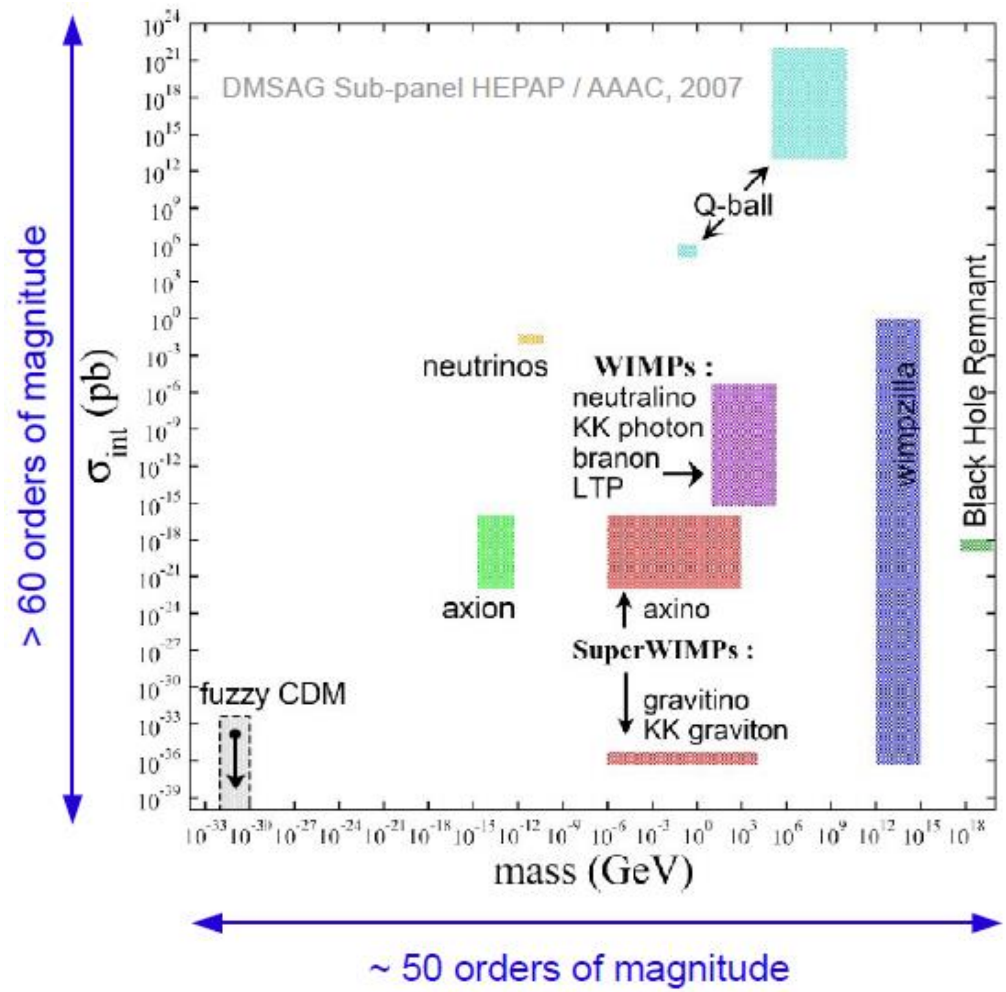
Theoretical candidates (today)



What is dark matter made of ?

- Dark Matter requires physics beyond the Standard Model of particle physics

- **Gravitationally interacting**
- Ω_{DM}=0.23 ; Ω_{Matter}=0.05
- **Stable** (or long-lived)
    - Cold (or warm), not hot
    - Structure formation, CMB
- **Non-baryonic**
    - CMB, Big Bang nucleosynthesys
- **Electrically neutral**

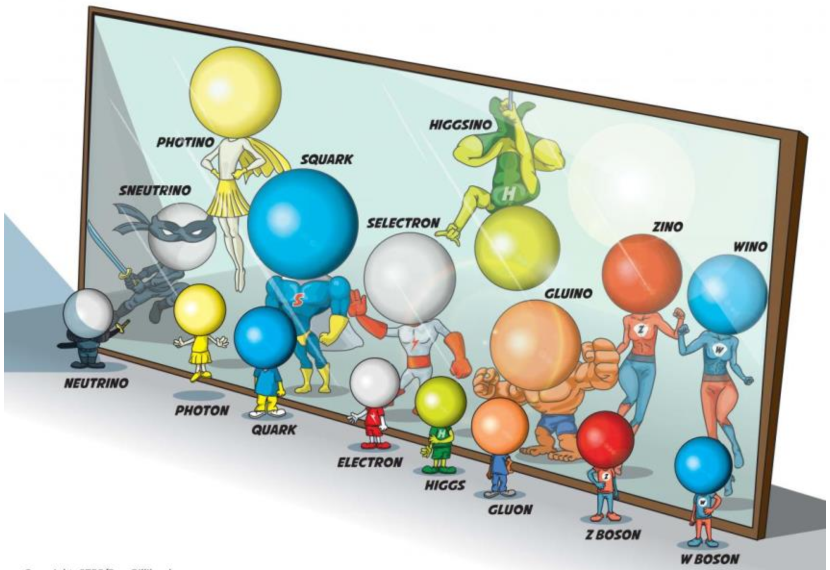


CANDIDATE LIST

- Conventional **neutrinos**
- "**Sterile**" neutrinos
- **Kaluza–Klein states**
- **Superheavy** particles, **Q-balls**
- **Magnetic monopoles**
- **WIMPs**
- **Axions**
- **Axion Like particles (ALPs)**
- **….**

Supersymmetry (SUSY) and WIMPs

- SUper SYmmetry (SUSY) is a proposed extension of spacetime symmetry that relates bosons and fermions. Each particle from one group is associated with a particle from the other, its superpartner (or sparticle), whose spin differs by a half-integer.
- If supersymmetric transformations exist, bosons and fermions are different manifestations of a unified state.
- Due to the fact that in the Standard Model there is no connection between fundamental bosons and fermions, the sparticles must be new objects.
- Among SUSY models, the Minimal Standard Supersymmetric Model (MSSM) represents the simplest one.

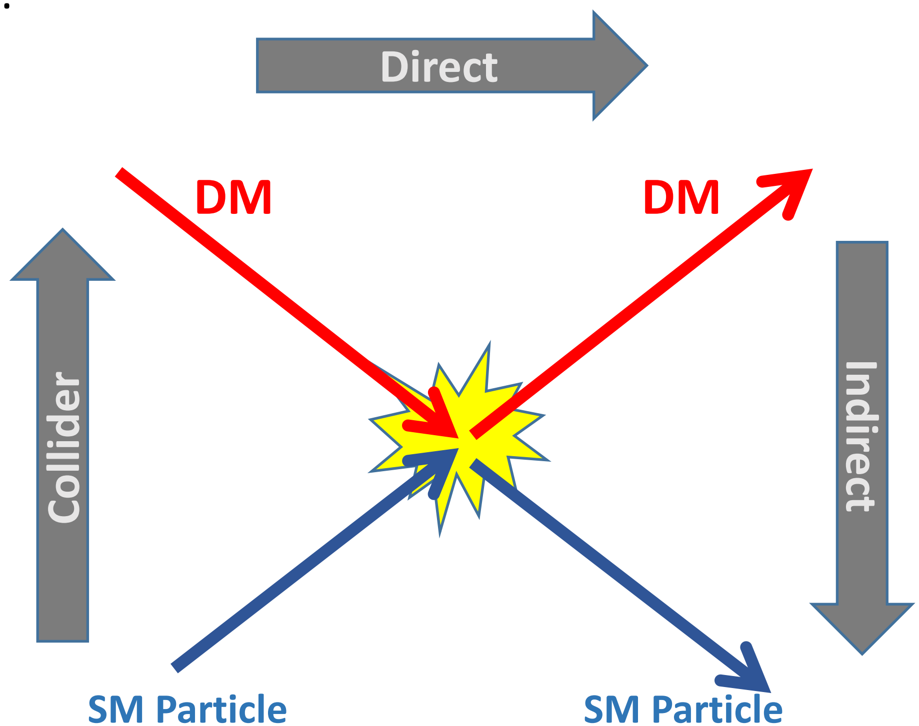


- The Lightest Supersymmetric Particle (LSP) is a well-motivated **WIMP** candidate .
- **<u>WIMPs (=Weakly Interacting Massive Particles)</u> are stable, colorless** (no strong interactions) and **electrically neutral** (no EM interactions). They interact with ordinary matter (in addition to gravity) with the coupling characteristic of weak interactions.
- Predicted WIMP masses are typically within the range from 10 GeV/c^2 to few TeV/c^2.
- At present, **NO INDICATION OF SUSY FROM LHC**! A real problem for this theory!

Interactions of WIMPs with Ordinary Matter

- WIMPs must have some unknown, small but finite coupling to ordinary matter and would be **directly detectable**.
- They can annihilate yielding normal particles into the final state, which are accessible to so-called **indirect experiments**.
- The amplitude for WIMPs annihilation into quarks is related to the amplitude for elastic scattering of WIMPs from quarks.

- Although unknown in strength, the WIMP-matter coupling has motivated different experimental strategies to search for such objects.
- Search strategies rely on the small, but nonzero, coupling of WIMPs to nuclei that would provide a finite (albeit small) event rate in the so-called **direct experiments**

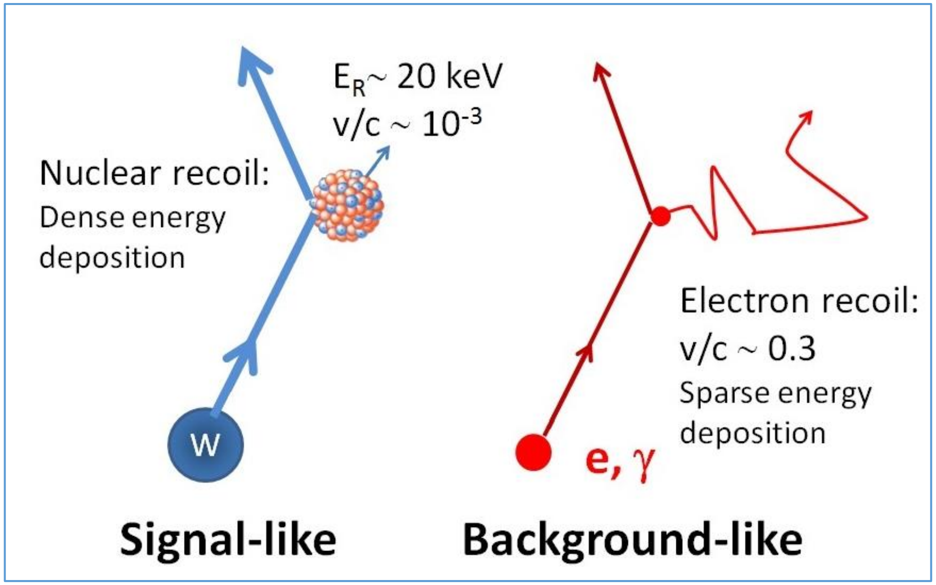


WIMP Dark Matter Direct Detection

- The idea that WIMPs can be detected by elastic scattering off nuclei in a terrestrial detector dates back to 1985.
- **Direct detections** look for interaction of DM particles in deep underground detectors.
- DM is expected to interact 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 I, Ge, Xn, Si... These detectors are sensitive in observing weakly interacting particles that recoil off the nuclei.

- DM particles must be heavy enough to affect the nuclei.
- If one assumes that WIMPs make up our Galaxy's halo with local density
  - ρ=0.3(GeV/c^2)/cm^{-3}
  - and virial velocity of 220 km/s
- Then, the local **spatial density** would be **(exercise:** verify by yourself!**)**:

$$n_\chi \sim 0.003\ (M\chi\ /100\ \text{GeV})^{-1}\text{cm}^{-3}$$



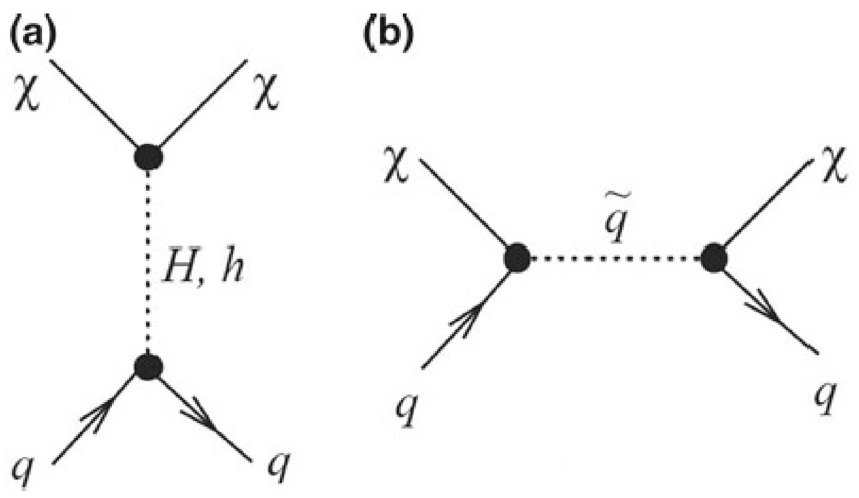
WIMPs Elastic Scattering

- The elastic scattering of a WIMP with a nucleus in a detector can be seen as the interaction of the WIMP with a nucleus as a whole, causing it to recoil.
- The energy of the recoil nucleus can be measured, if large enough.
- The WIMP-nucleus elastic scattering **cross-section** is the quantity under study **(=unknown)** in direct experiments.
- This cross-section also determines the rate at which particles from the Galactic halo accrete onto the Sun (or other massive objects) and contributes to the signal yield in the indirect detection experiments.

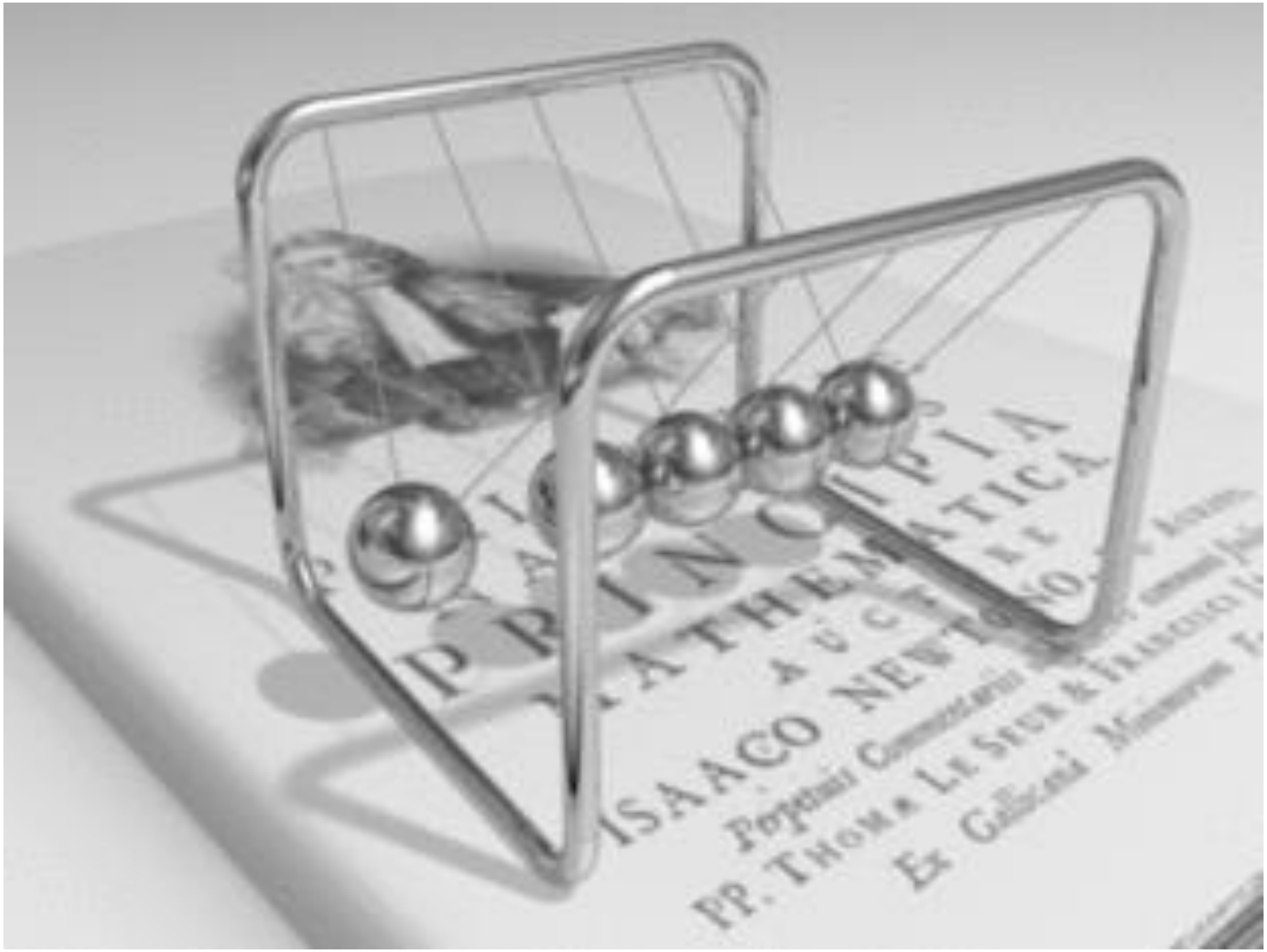
- The interaction of WIMPs with quarks and gluons (=*partons*) of the nucleon is quantified in Feynman diagrams (see Fig.)

Two cases are usually considered:

- the spin-spin (or ***spin-dependent***) interaction and
- the scalar (or ***spin-independent***) interaction.



Direct Detection of Dark Matter



Direct Detection of Dark Matter

- WIMPs can be detected by elastic scattering off nuclei in a terrestrial detector (1985)
- The Earth's motion around the Sun would produce an annual modulation in the expected signals (see later)
- In the scattering to a nucleus of A, the energy transferred to the recoiling nucleus is

$$E_R = \frac{p^2}{2m_A} = \frac{m_{r_A}^2 v^2}{m_A}(1 - \cos\theta), \qquad (14.19)$$

- Numerically, assuming $m\chi$ = 100 GeV/c^2, v = $10^{-3}c$ and a nucleus with $A \sim 100$

$$\langle E_R \rangle = \frac{1}{2} m_\chi \overline{v}^2 \sim 50\,\mathrm{keV}\ . \qquad (14.20)$$

- Specialized detectors able to measure recoils of such considerably lower energy, and to distinguish them from background, may make direct detection possible.
- The event rate in a detector depends on many input factors:
  1. **the nature of the interacting particle, related to the unknown scattering cross section (spin-dependent or independent)**
  2. **the nuclear form factors of the detection material;**
  3. **the astrophysical density distribution of WIMPs and their velocity distribution**
  4. **the response of the detector as a function of the nucleus recoil energy**

Direct Detection of Dark Matter

$$R = N_T \cdot \frac{\rho_0 \cdot \overline{v}}{m_\chi} \cdot \sigma_{\chi A}^{SI}$$

- The event rate for spin-independent interaction would be:
- That means that, under specific conditions on the velocity, by measuring the rate R we can have measures (or limits) on the **cross section and DM mass**.
- From the above relation, under reasonable conditions for the cross section and for **argon** and **xenon** detectors, the event rates are on the order of $\sim 10^{-4}$–10^{-3}/kg/day.
- Direct-detection experiments measure the number of signals equivalent to a given nuclear recoil E_R/ day/kg of detector material (see figure)
- Many background sources can simulate events with a deposited energy equivalent to E_R.

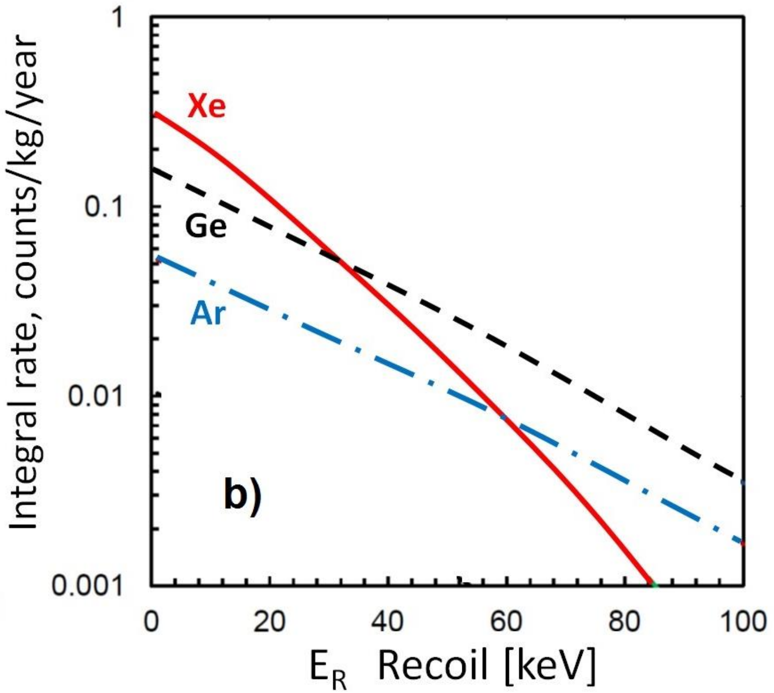


Figure: Integral energy spectrum of a spin-independent elastic scattering WIMP-nucleus for four different nuclei, assuming perfect energy resolution of the detector, assuming $m\chi$ = 100 GeV/c^2, $\sigma_0 = 10^{-45}$ cm^2

Direct Searches of Dark Matter

- To observe WIMPs, detectors with a **low energy threshold**, an **ultra-low background noise** and a **large target mass** are mandatory
- In a detector, the kinetic energy of a nucleus after a WIMP elastic scattering is converted into a measurable signal: depending on experimental techniques, the signal corresponds to **(1)** ***ionization*****, (2)** ***scintillation light*****, (3)** ***vibration quanta (phonons)***.
- The main experimental problem is to distinguish the genuine nuclear recoil induced by a WIMP from the huge background due to environmental radioactivity.
- Simultaneous detection of two observables strengthens the discrimination against background.
- Granular detectors and/or good timing and position resolution are needed.
- Regardless of the experimental technique, DM detectors are located at a deep underground site to reduce the flux of CR muons and neutrons

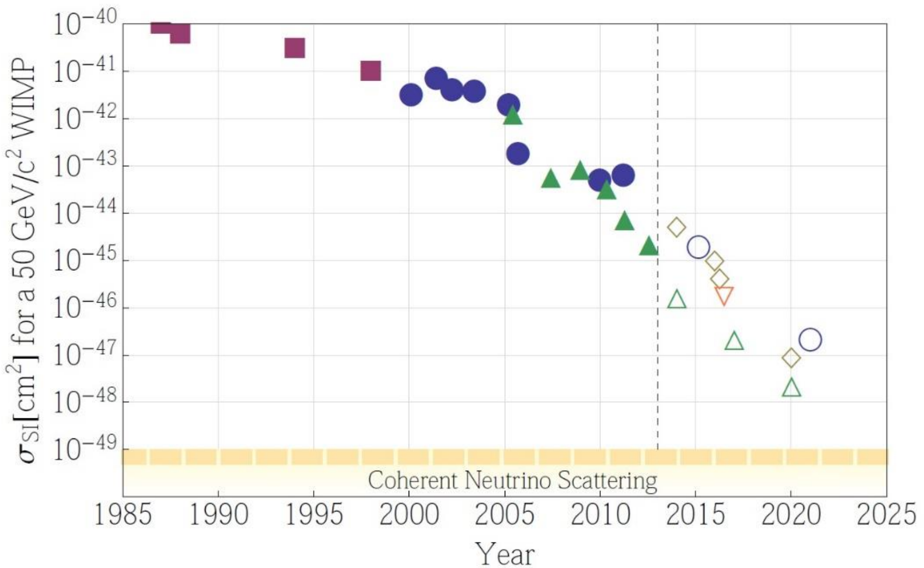


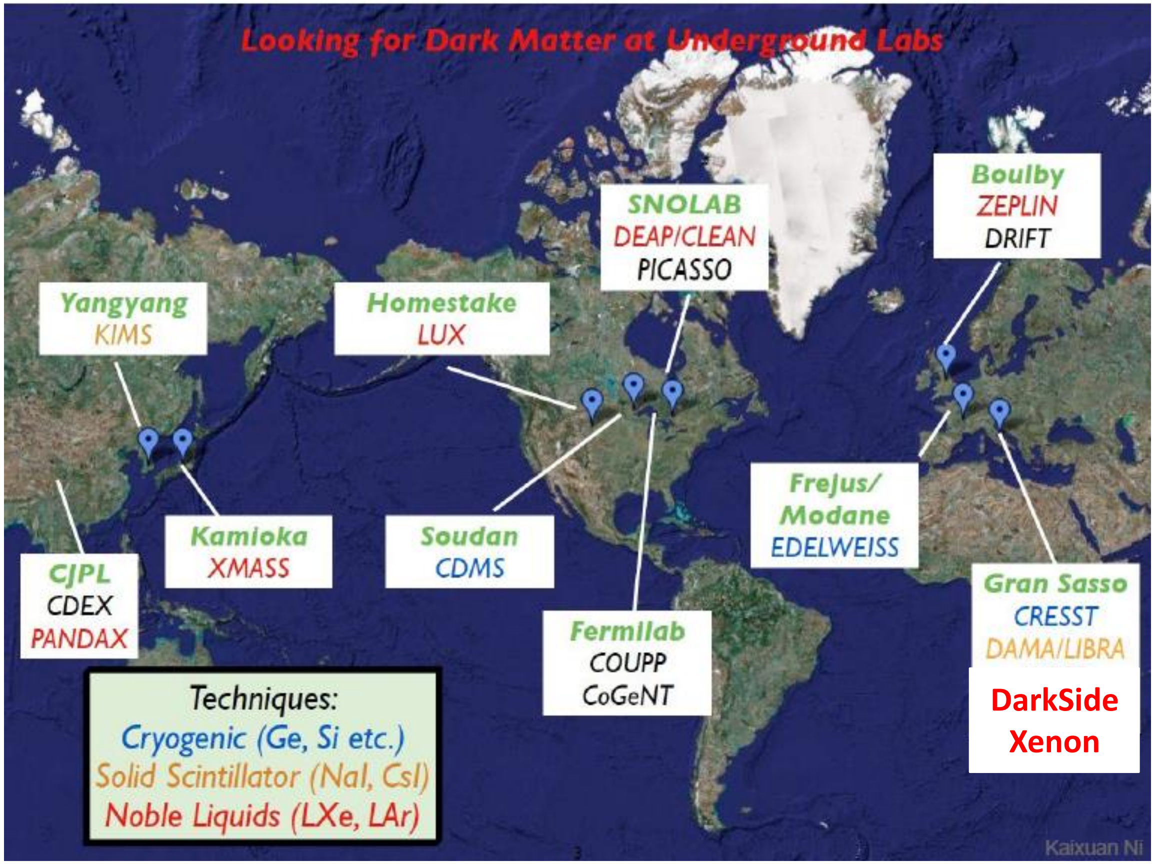
***Fig. 14.6** Projected evolution with time of SI WIMP-nucleon cross-section limits for a 50 GeV WIMP. The symbols used to denote the different technologies*

Detectors for direct Searches of Dark Matter

- Direct detection experiments have made huge progress in the last three decades
- Three principal experimental methods have been developed

1. **Solid state cryogenic Detectors)**
2. **Scintillation crystals (NaI, …)**
3. **Noble Liquid (or two-phases) detectors**

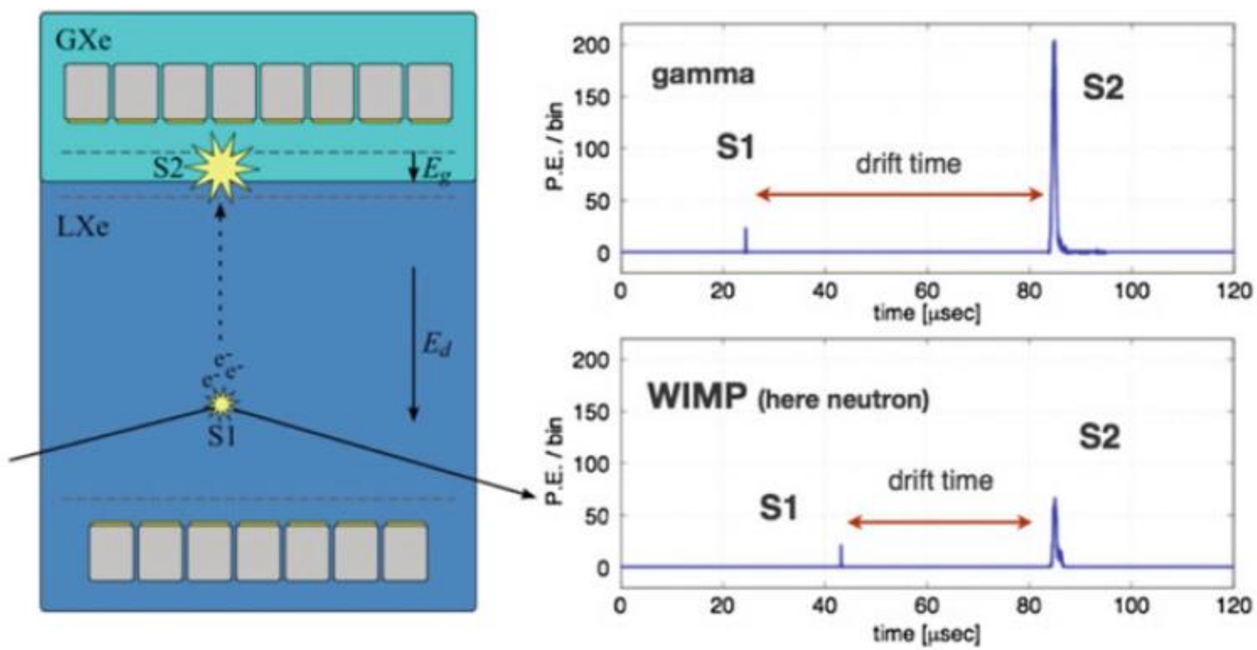
Note (2019): «Orange» detectors in only one side!



Noble Liquid (or two-phases) detectors

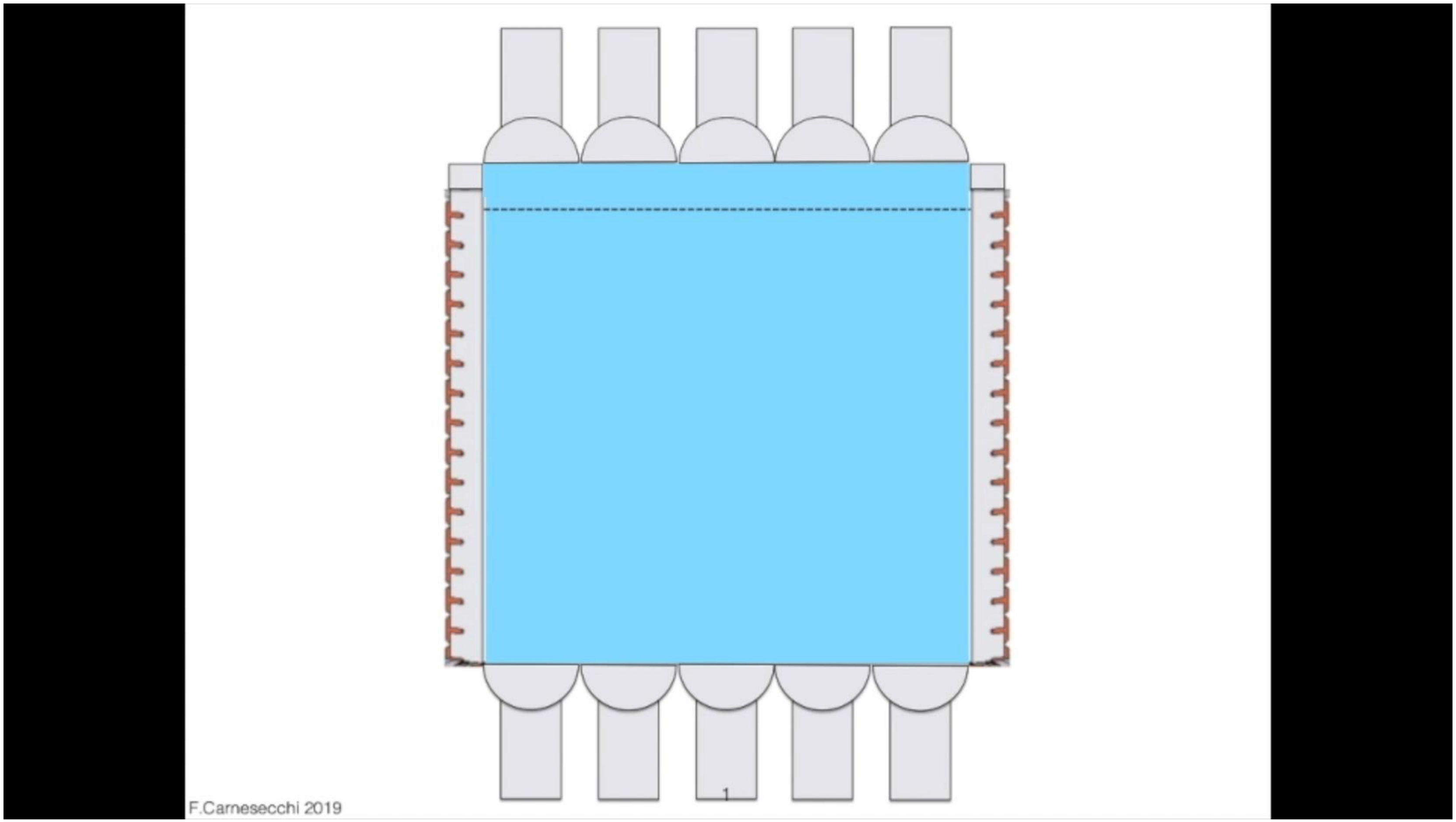
- Noble elements in liquid state such as argon (A = 40) and xenon (A = 131) offer excellent media for building homogeneous, compact, and self-shielding detectors.
- Liquid xenon (LXe) and liquid argon (LAr) are good scintillators and ionizers in response to the passage of radiation.
- LXe and Lar have the relative facility of scaling-up to large masses.
- They can operate in single readout mode as a scintillation-only detector: the problem is the rejection of electron recoils on an event-by-event basis.
- Two-phase time projection chambers (**TPC, see Figure)** have also been developed

Fig. 14.7 Schematic of a xenon two-phase TPC, showing the recorded signals for a γ -ray interaction and a WIMP. The ratio S2/S1 is used to discriminate between electron and nuclear recoils



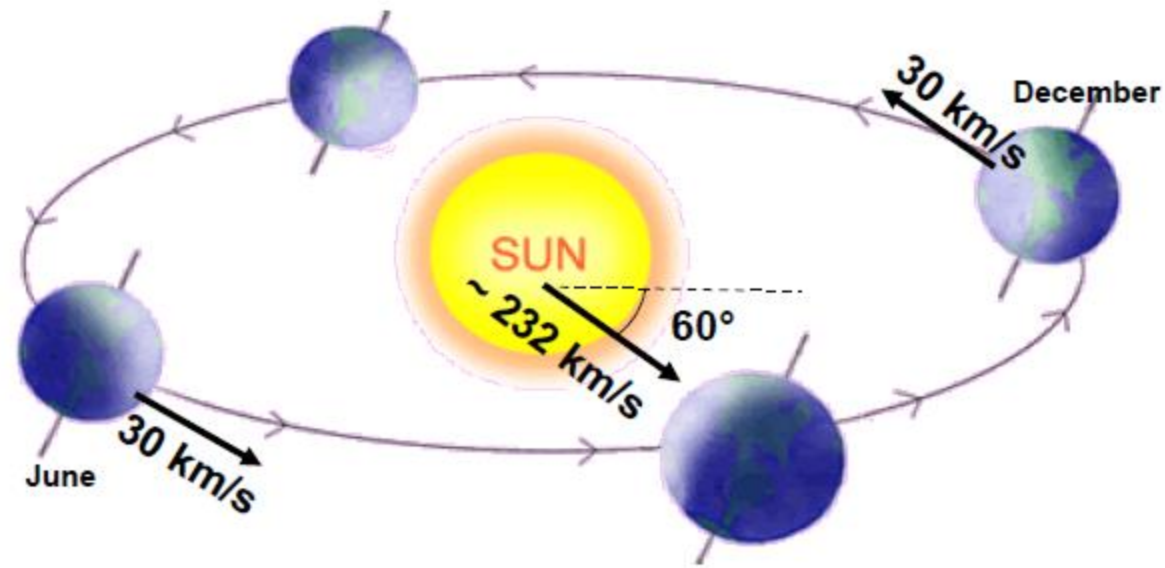
Noble Liquid (or two-phases) detectors

https://web.infn.it/darkside-bologna/index.php/it/



Annual modulation of WIMPs

- A Different approach: infer the presence of DM from annual modulation
- As the Earth orbits the Sun, it changes its direction in the DM halo thus altering the DM flux into the detector.
- The above effect leads to an annual modulation in the detected recoil rate.
- **Only one dedicated experiment** takes this approach, DAMA, and that have reported an annual modulation
- DAMA uses a superb (in terms of background) scintillation crystals (NaI)

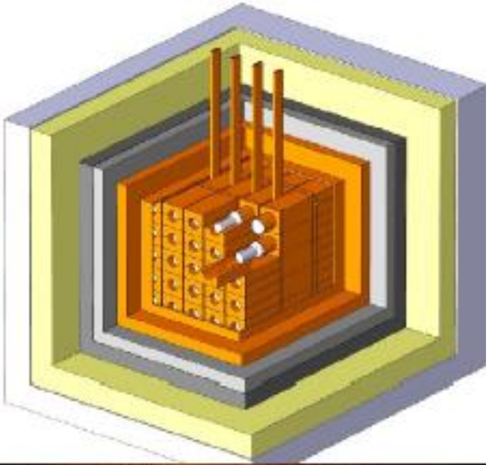


The experiment using scintillation crystals

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

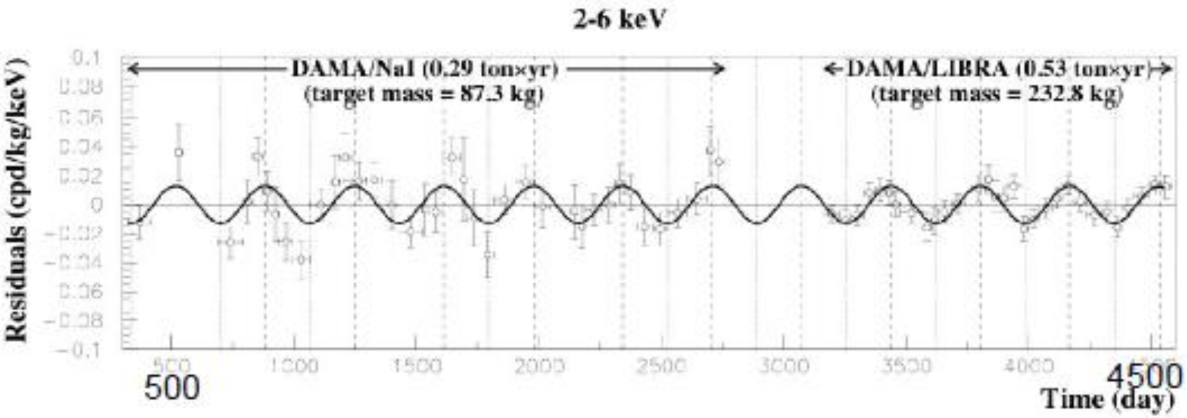


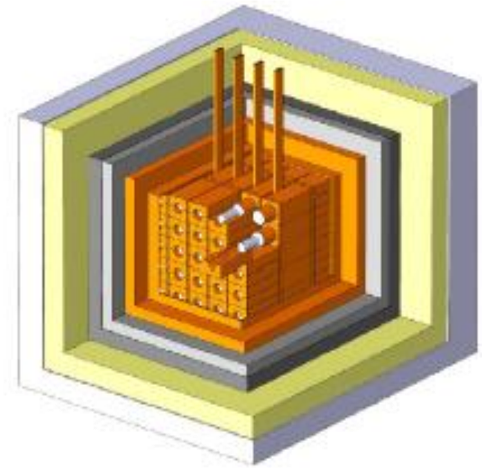
Uwe Oberlack

A DM Signal ?

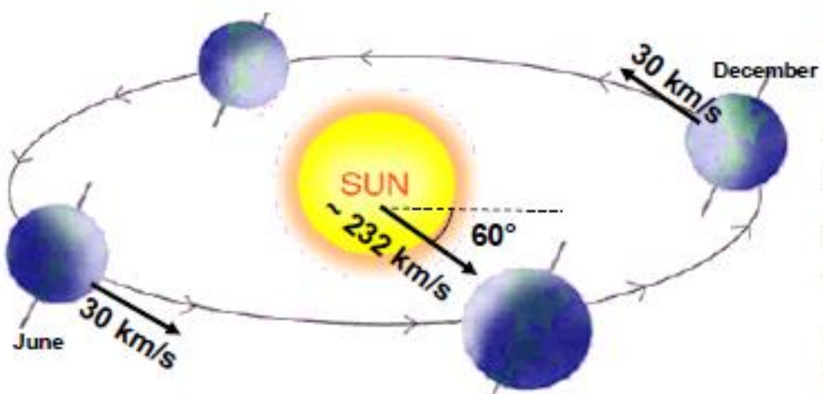
DAMA/LIBRA Annual Modulation

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

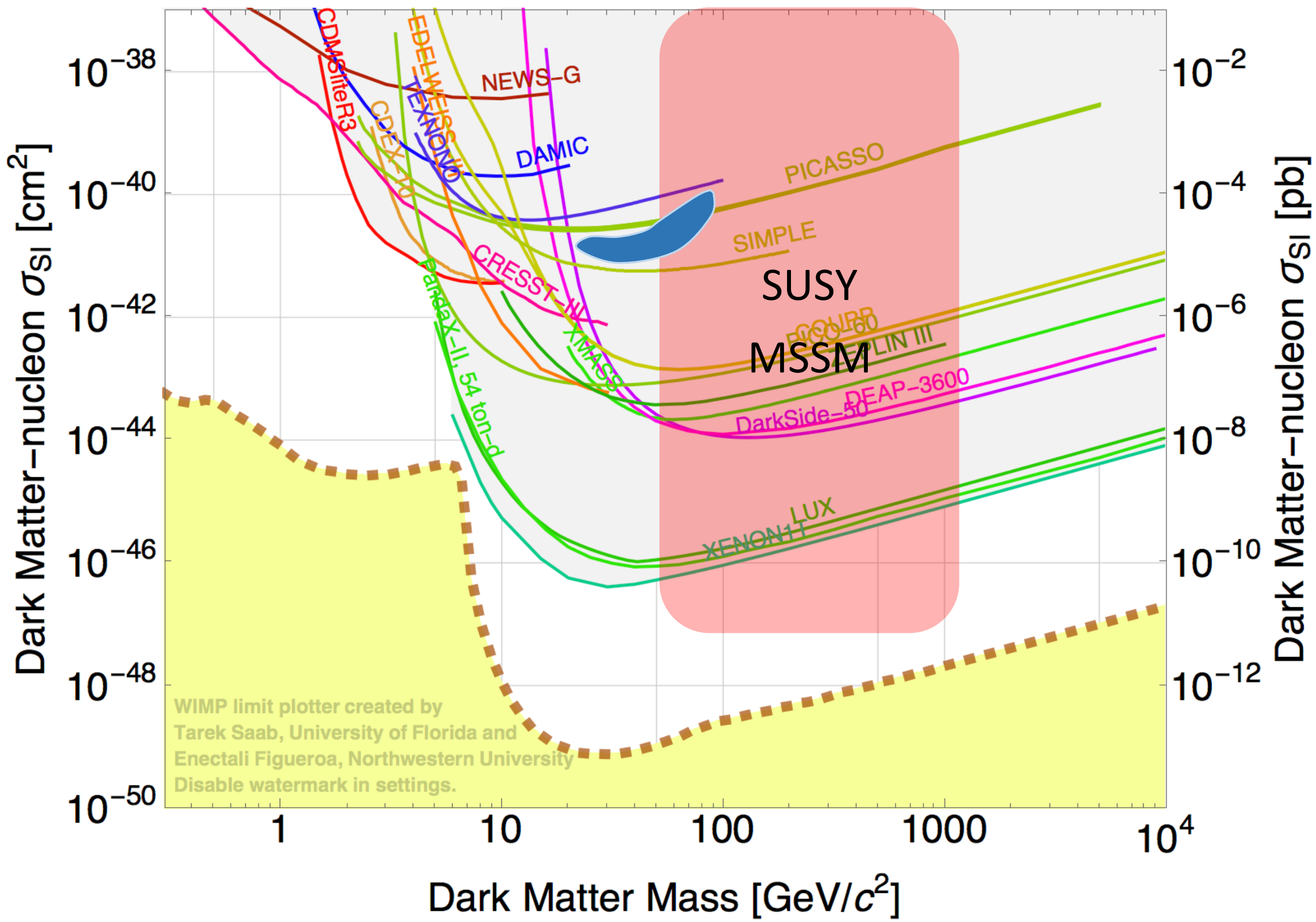
- Modulation in 2-6 keV single hits: 8.9 σ
- Mostly in 2-4 keV, ~0.02 cts/d/kg/keV
- Total single rate ~1 cts/d/kg/keV
- Standard DM distribution: < ~5% modulation
- Period & phase about right for DM.
- No annual modulation in 6-14 keV.
- No annual modulation in multiple hits. (which?)
- **DM detection?**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

Summary of direct searches

- WIMPs could have scalar, σ^{SI} , and/or spin-dependent, σ^{SD} interactions with nuclei
- Experimental results are discussed in terms of either interaction type.
- Figure illustrates the current best limits on WIMP σ^{SI} vs. WIMP mass. Null results from different experiments yield upper limits plotted as lines.

- The parameter space above a line is excluded.
- The yellow region will be subject to the background due to neutrino interactions.

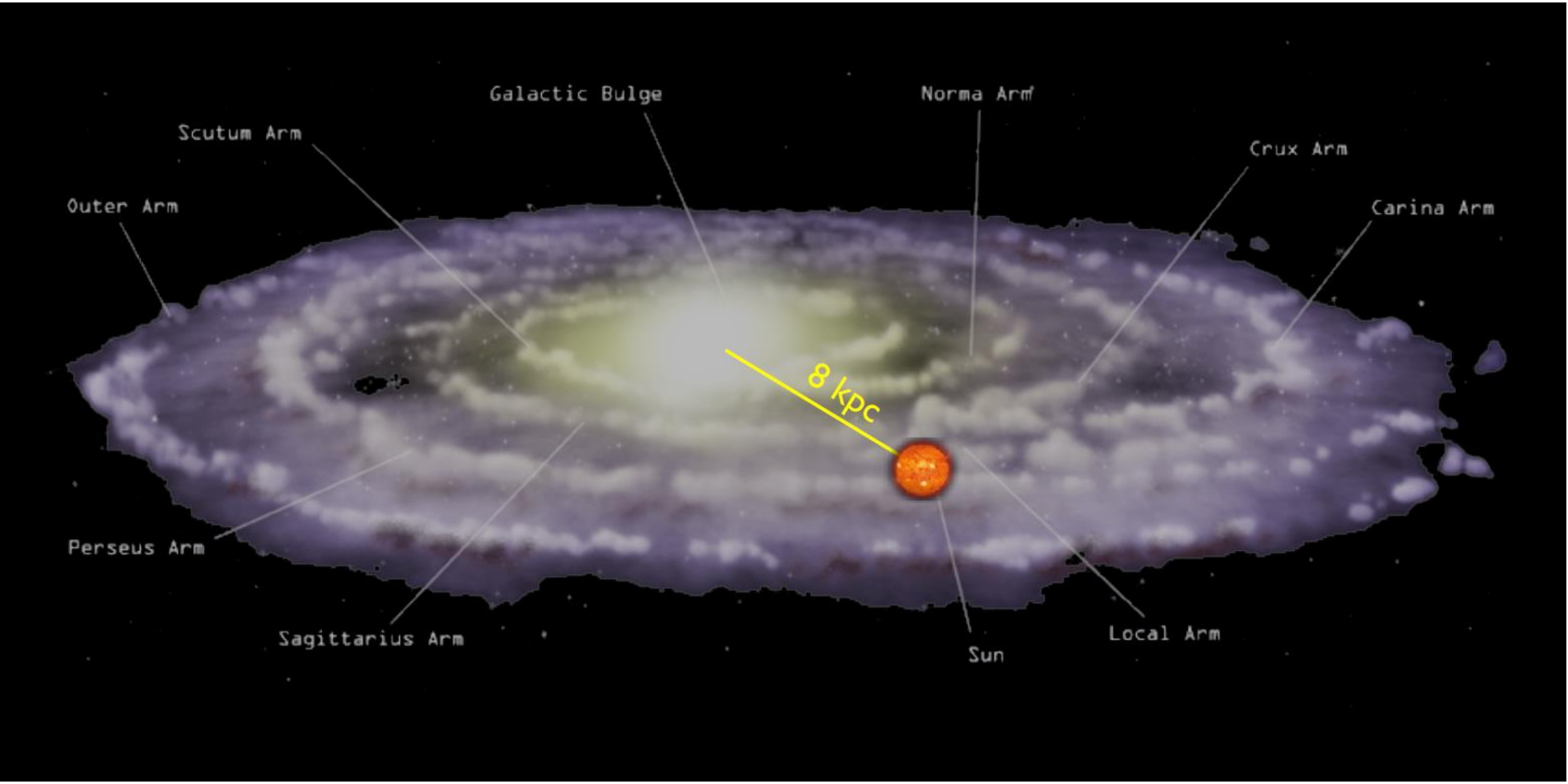
- The DAMA region (?)



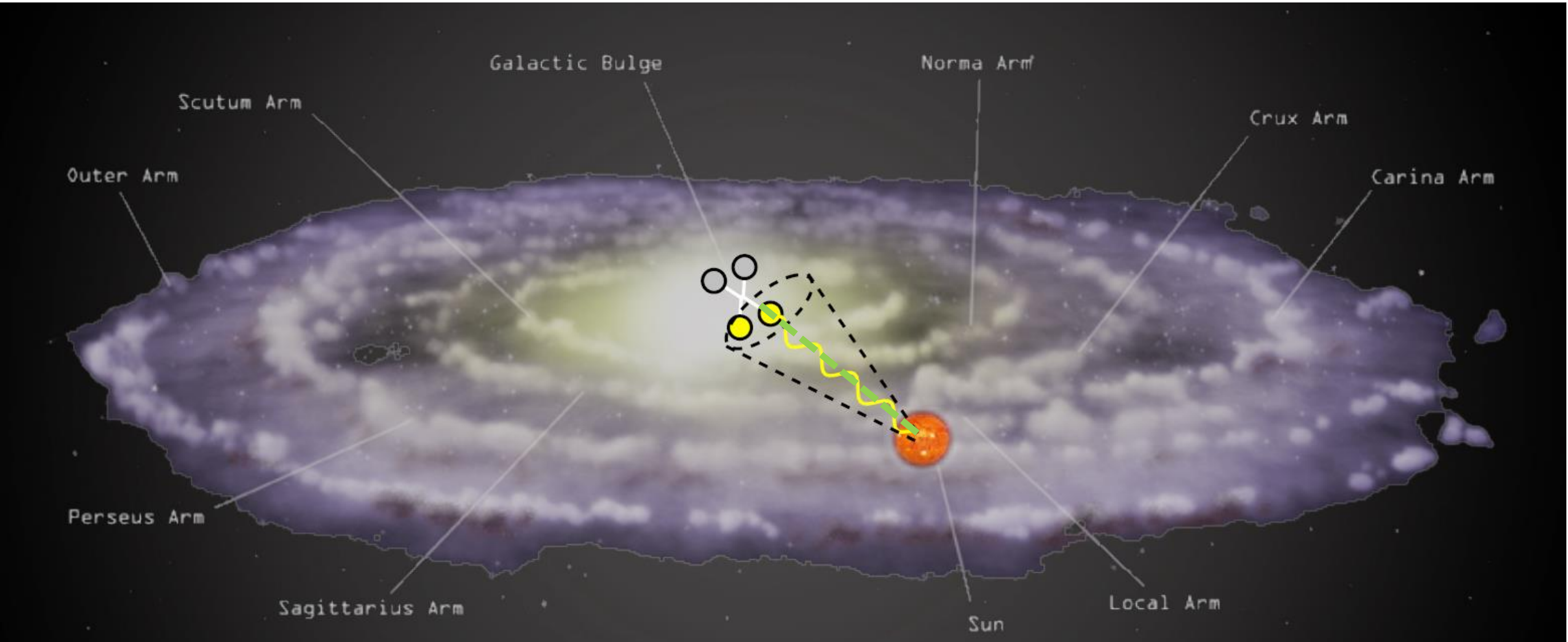
Indirect Searches for WIMPs

- WIMPs would annihilate into standard model particles with the cross-section (14.10) to explain cosmological observations.
- Today, WIMPs annihilation continues, and may be large enough to be observed indirectly if the end products include photons, neutrinos, electrons, protons, deuterium, and their corresponding antiparticles.
- There are many indirect detection methods being pursued. The difficulties concern the backgrounds and systematic uncertainties that vary greatly from one method to another.
- The most exploited methods refer to:
  - **Neutrinos** from annihilations in the core of massive objects in wich WIMPs can be accumulated (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 IAC telescopes: MAGIC, HESS, VERITAS

Indirect detection



Indirect detection

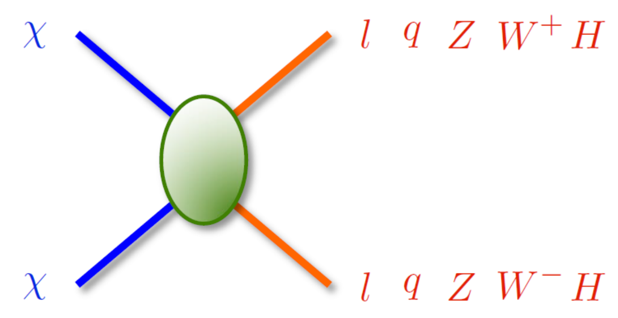


$$DM\,DM \to W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma \;, \nu$$

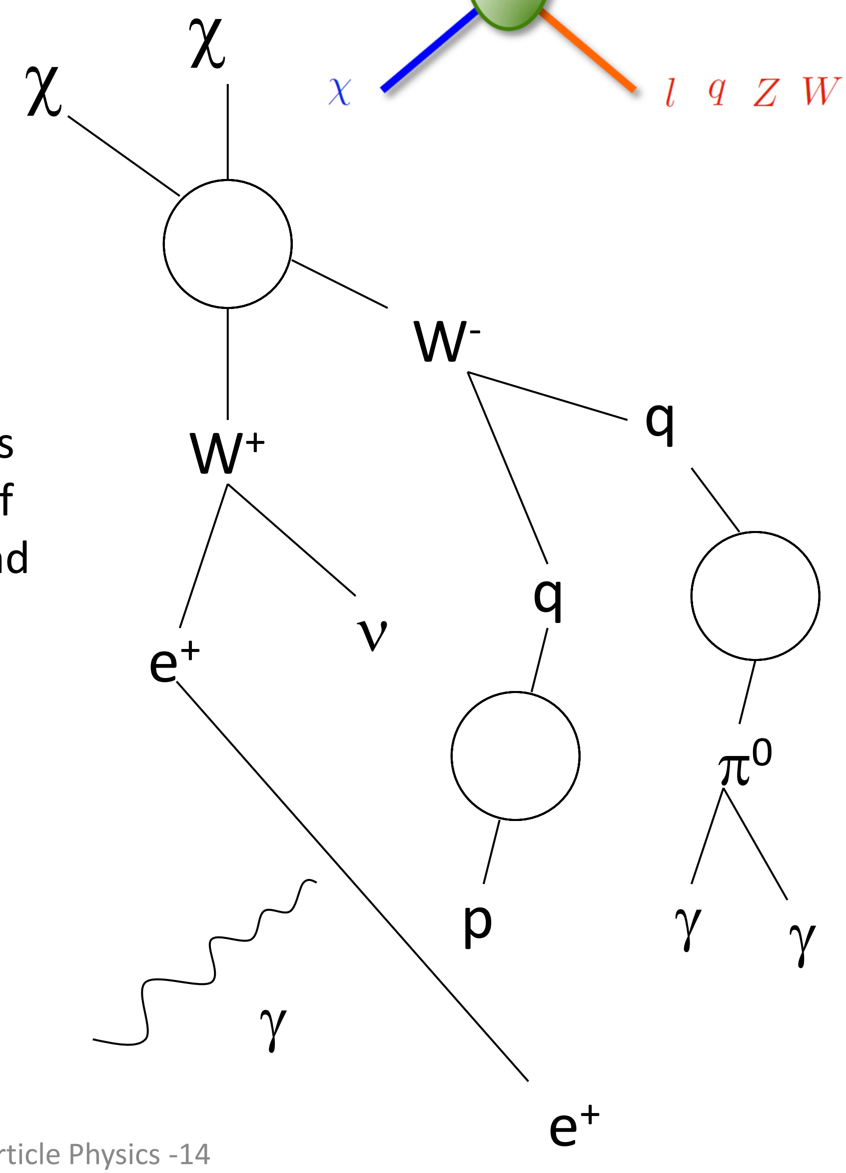
$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma \;, \nu$$

Credit: http://www.marcocirelli.net

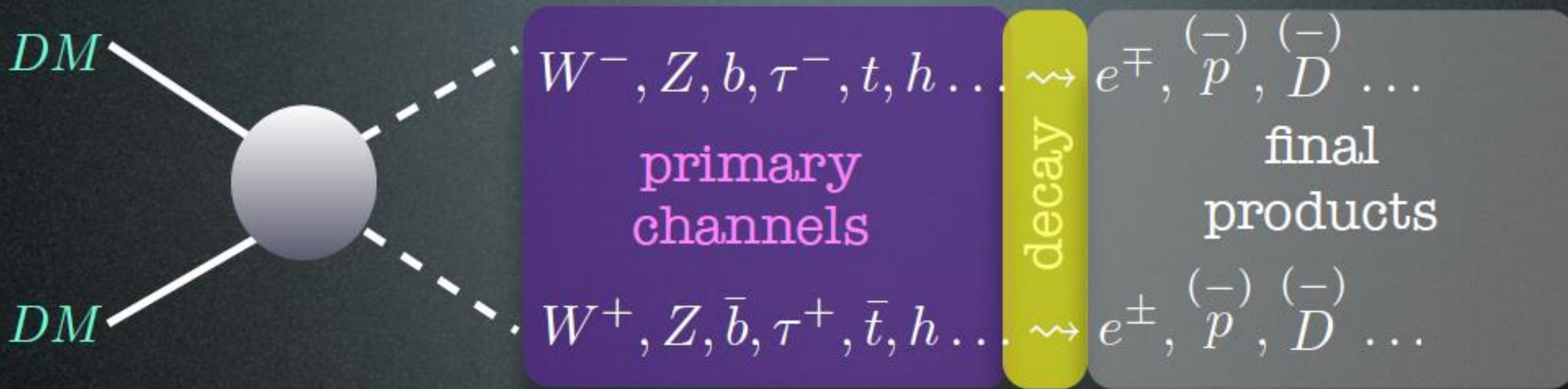
DM annihilation to SM particles

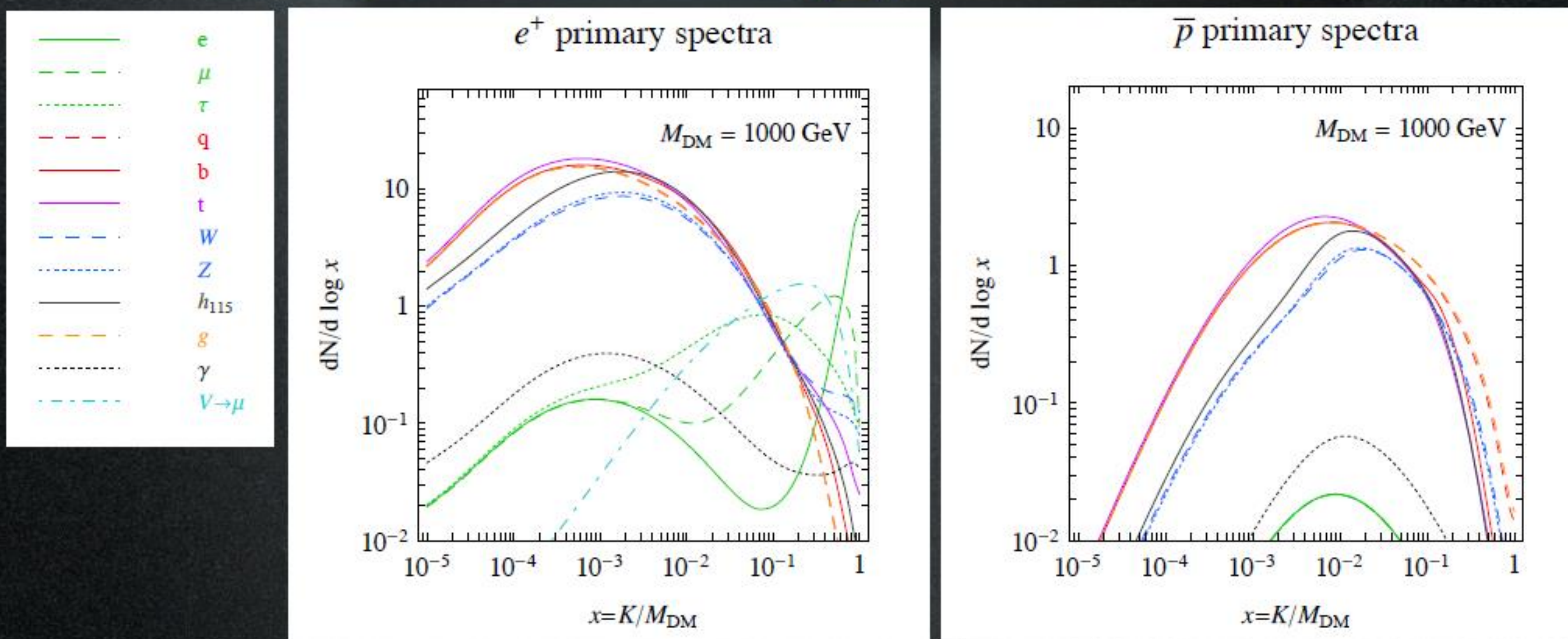


- DM can annihilate into charged particles in the final state, which add to the cosmic radiation from astrophysical origin.
- **WIMP Annihilation. F**inal states include heavy fermions, gauge or Higgs bosons
- **Fragmentation/Decay** Annihilation products decay and/or fragment into combinations of electrons, 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



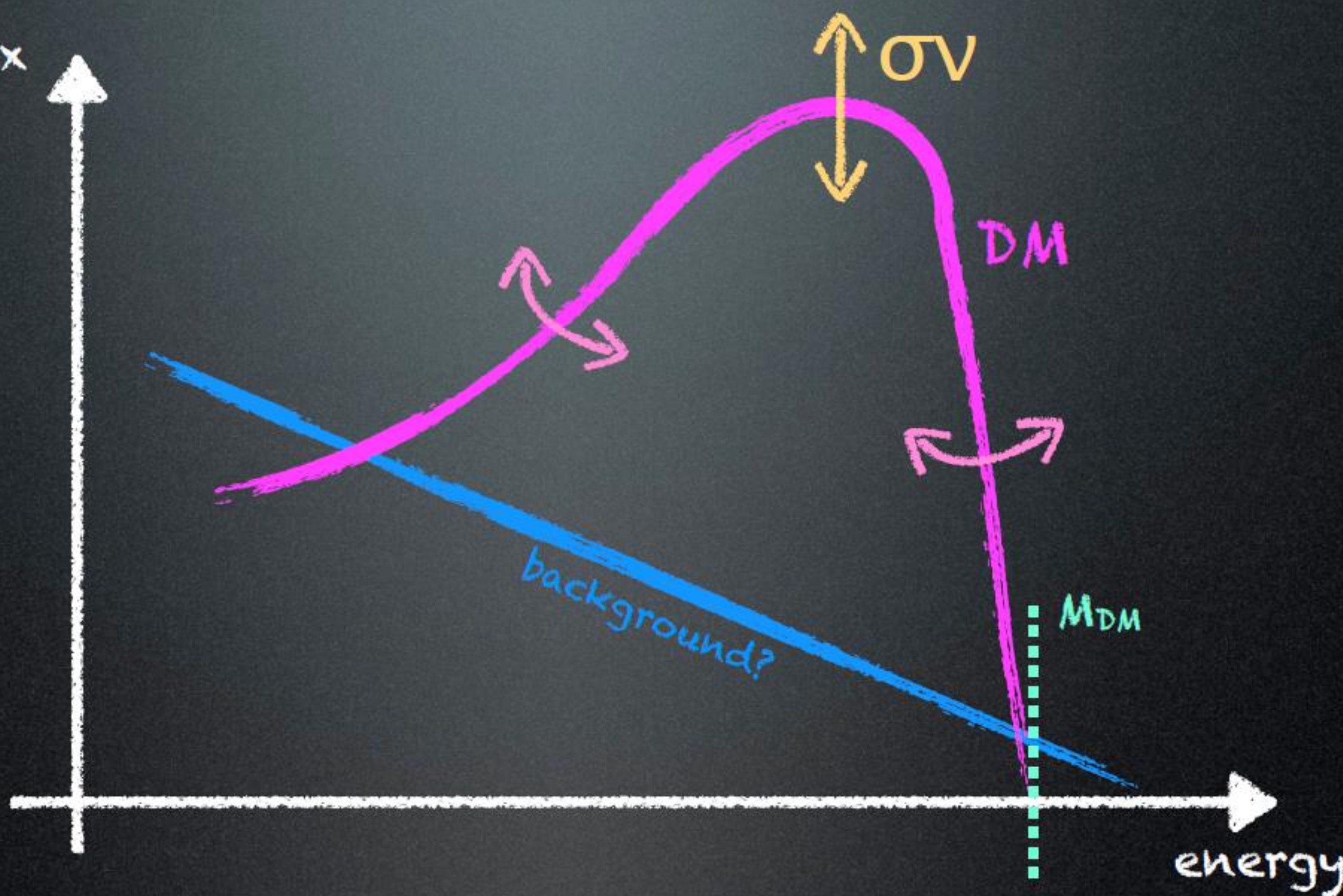
Indirect Detection: basics





Credit: http://www.marcocirelli.net/

Fluxes at production



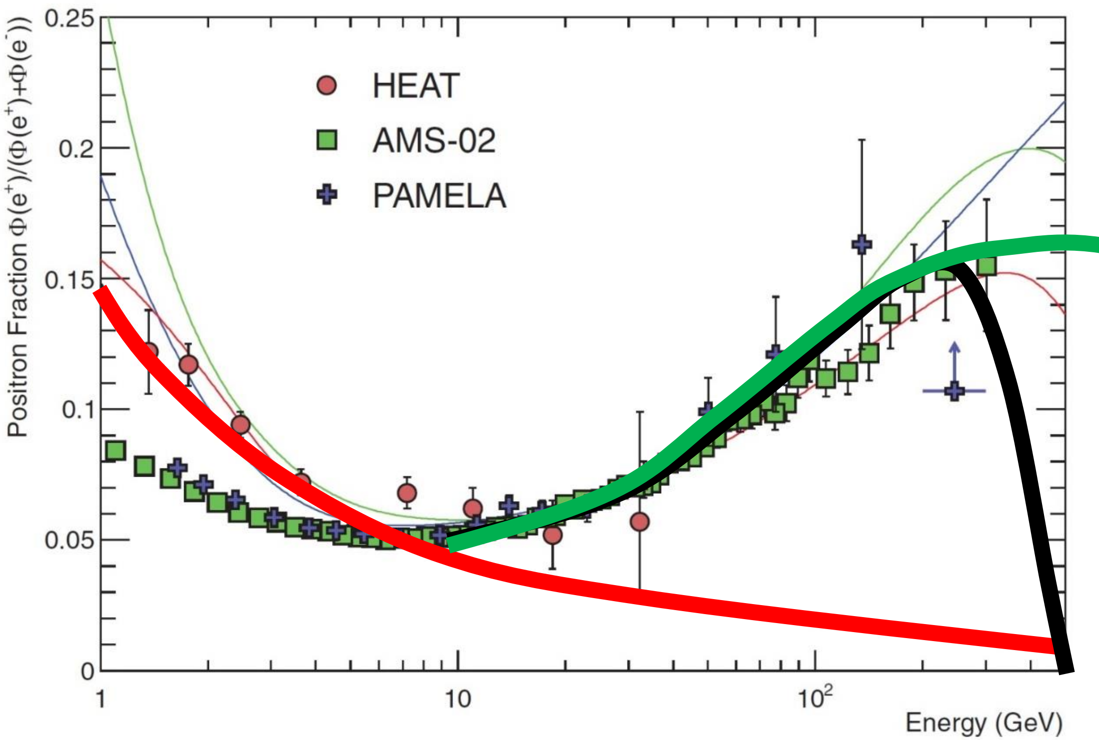
So what are the particle physics parameters?

1. Dark Matter mass
2. primary channel(s)
3. cross section

Credit: http://www.marcocirelli.net/

The positron fraction: an open question (Chap. 3)

- The positron-fraction (on average, 10% of e-) spectrum does not exhibit fine structures and steadily increases in the region between 10 and 250 GeV (AMS-02 data)
- Since positrons are always created in pair with an electron, **about 90% of the observed electrons must be of primary origin**.
- This increase of e+ fraction is well above that expected from "propagation models" (red); some changes will be requested under astrophysical assumptions (green), for instance the presence of near pulsars (Chap. 6)



- More exotic models have been carried out (dark matter)
- Further data on higher energies can be disentangle between hypotheses

Neutrinos from Earth and Sun

- **Capture**

Galactic DM particles that cross the Earth and the Sun, can interact with the nuclei in these bodies and loose enough energy to remain gravitationally Captured (v< escape velocity)

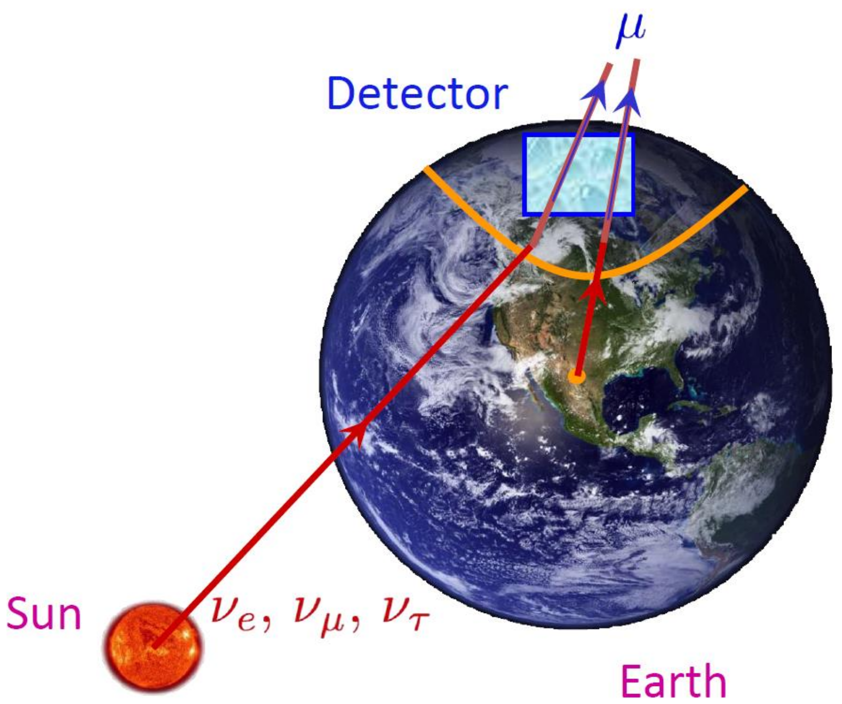
- **Accumulation**

After subsequent interactions they tend to drop into the innermost parts of the Earth and the Sun, where they accumulate

- **Annihilation**

When the energy density in the inner parts of the Earth and the Sun increases enough, they may start to annihilate

- **Neutrino signal**



Example of result (search from the Sun direction)

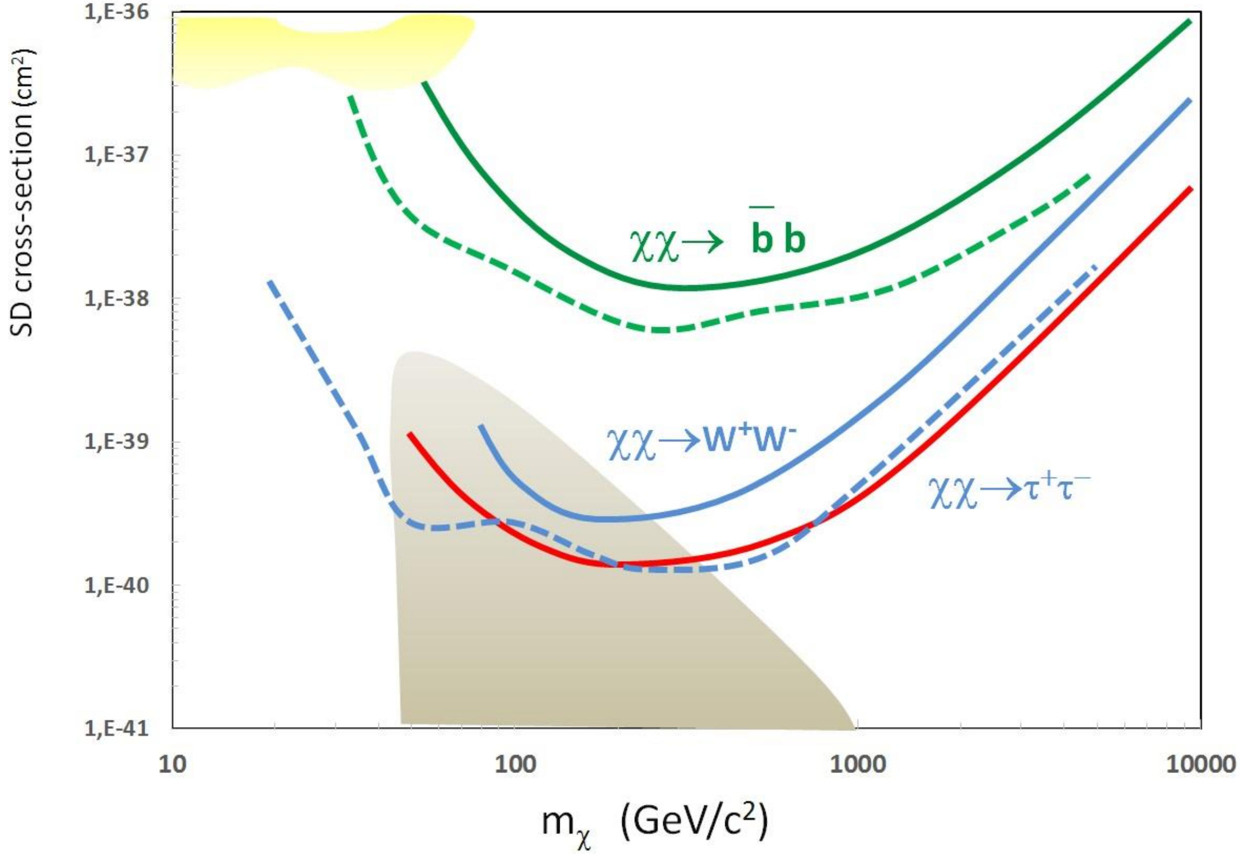
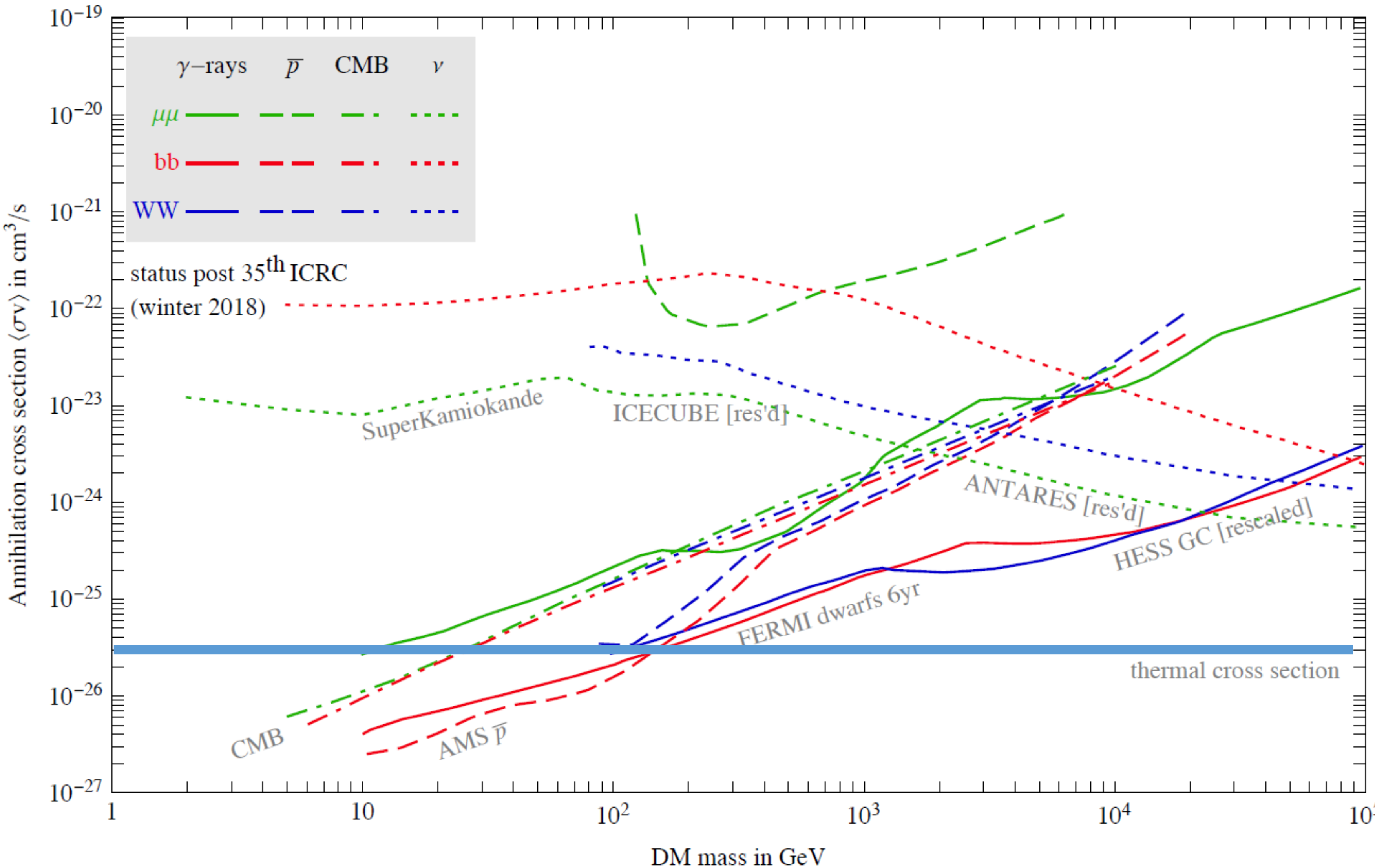


Fig. 14.9 Upper limits (at 90% C.L.) on WIMP-nucleon σ^{SD} vs. WIMP mass three self-annihilation channels. The limits are obtained by the ANTARES (full lines) and IceCube (dashed lines) neutrino telescopes searching for an excess of high-energy ν_μ from the direction of the Sun. The bottom colored region represents the space of parameters allowed by MSSM and the yellow region at the top left the DAMA allowed region.

Comparing all indirect experiment bounds (2020)

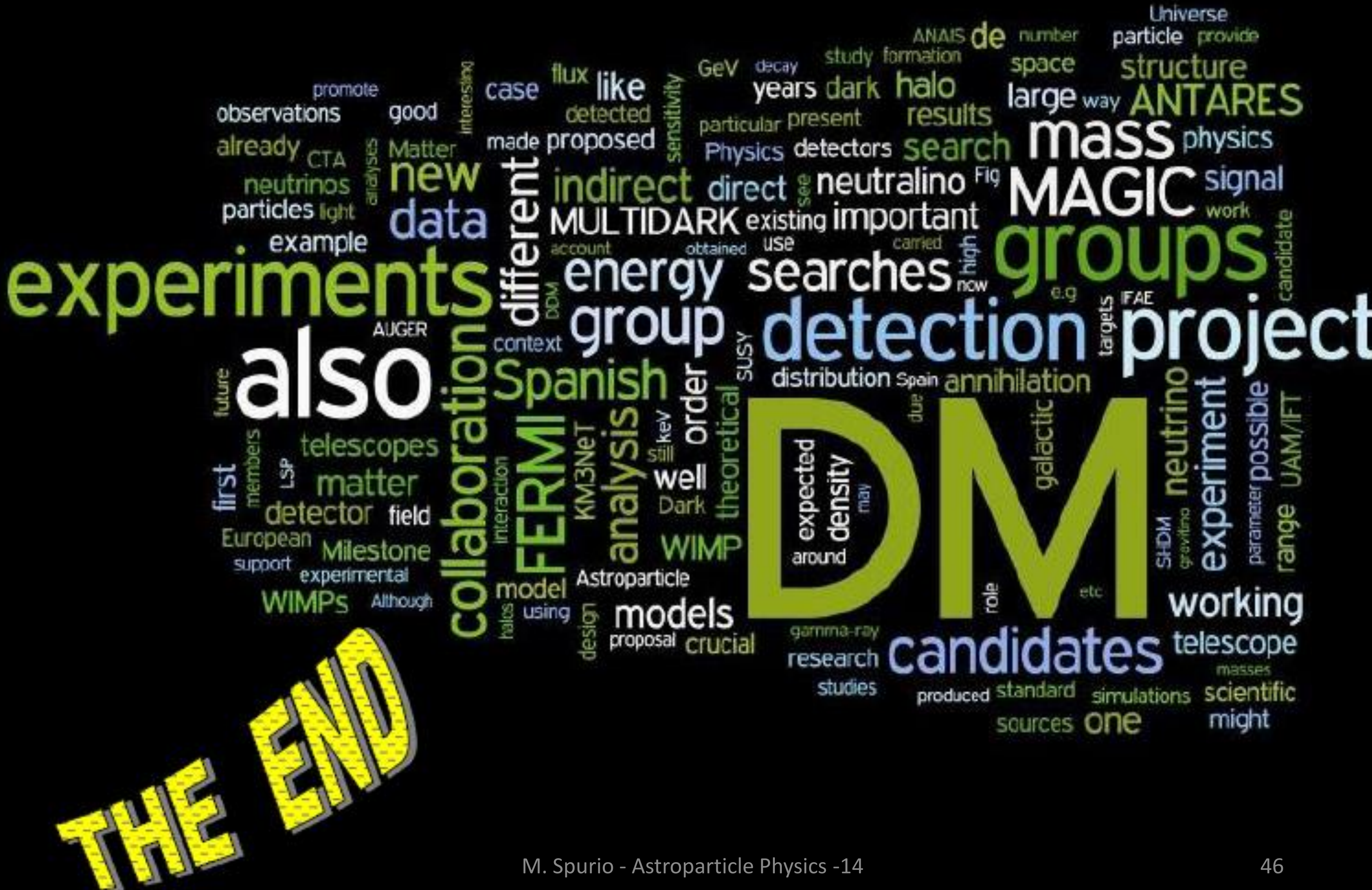


Dark matter

- The discovery of the Higgs boson in 2012 completed the SM scenario.
- However, there are deficiencies and open questions related to experimental data that the SM cannot explain (the neutrino mass problem, the CP problem, the gauge hierarchy problem, dark matter and dark energy…).
- There are strong motivations for the existence of Dark Matter both from astrophysical and cosmological (not covered!) point of view.
- However, no DM candidate has been seen yet in direct and indirect searches, and also in accelerators
- The DM problem requires physics beyond the SM.
- In the last 30 years, SUSY theories seem to offer a natural solution.
- SUSY offers some leading DM candidates and provides guidance for DM searches.
- ***Warning***: New particle searches at LHC are not equivalent to DM searches: who guarantee that a new particle is the component of the missing matter of the Universe?

What next?

- Concerning WIMPs:
  1. even after negative searches results, they are still appealing (in particular in the multi-TeV range)
  2. searches are complementary and still have ground to cover
- Direct and indirect searches are of fundamental importance
- A necessary improvement need a better knowledge of astrophysics background. **Multimessenger observations needed**
- The lack of SUSY signals at the LHC and the increasingly stronger limits from direct/indirect searches have weakened the argument for WIMPs as the solution of the hierarchy problem.
- **What will occur if both, accelerator, and astroparticle experiments for WIMP give null evidence of supersymmetric partners?**
- The evidence for DM is so strong that a plethora of new models of particle DM has been generated that must be tested by the new generation experiments.
- **WORK FOR YOU.**



Universe
ANAIS de number particle provide
study formation
promote interesting flux like sensitivity GeV decay space structure
case years dark halo
observations good detected large way ANTARES
particular present results
already CTA analyses Matter made proposed Physics detectors search mass physics
neutrinos new indirect direct see neutralino Fig MAGIC signal
particles light data different MULTIDARK existing important work
example account obtained use carried high candidate
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AUGER group detection project
targets IFAE
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THE END