DARK MATTER (2)

A long history, … not finished

Philippe Miné, Laboratoire Leprince-Ringuet, France

NEUTRINOS

Electron antineutrinos are produced by nuclear reactors (beta decay)
first detected by Cowan and Reines in 1956

Electron neutrinos from Sun are detected by underground experiments since the first attempts in the 1960s by Davis (Nobel prize 2002)
at the Homestake Gold Mine. The experiment was running from 1970 to 1994.

The solar neutrino mystery was definitively solved by proof of oscillation in SNO (Sudbury Neutrino Observatory in 2001.

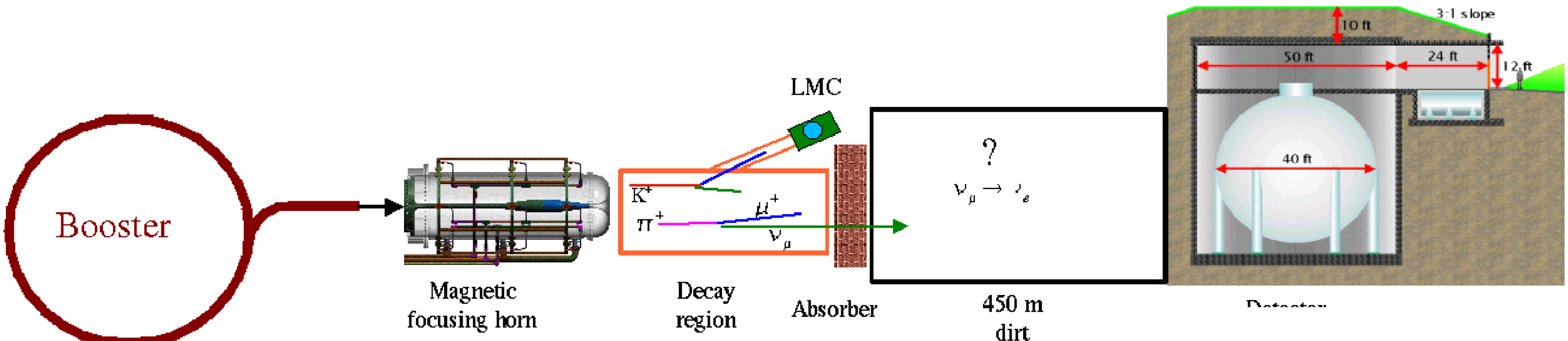
24 electron neutrinos and antineutrinos from supernova 1987A were observed by 3 experiments

The 3 flavors of neutrinos and antineutrinos are produced by high energy accelerators

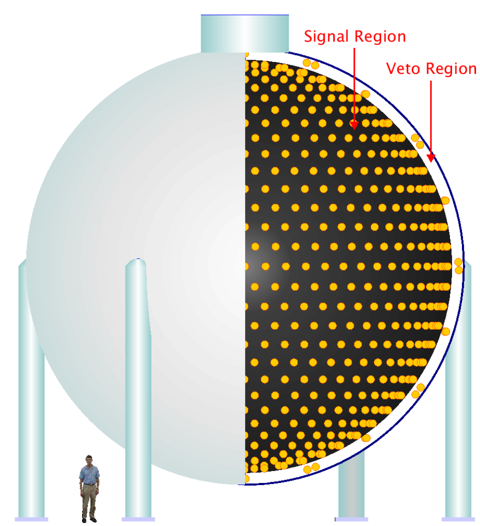
These “ordinary” neutrinos have too light mass to account for all dark matter

NEW NEUTRINO SEARCH

Sterile neutrinos in reactor and accelerator, produced by oscillation
MiniBooNE at Fermilab 2018



MiniBooNE Detector

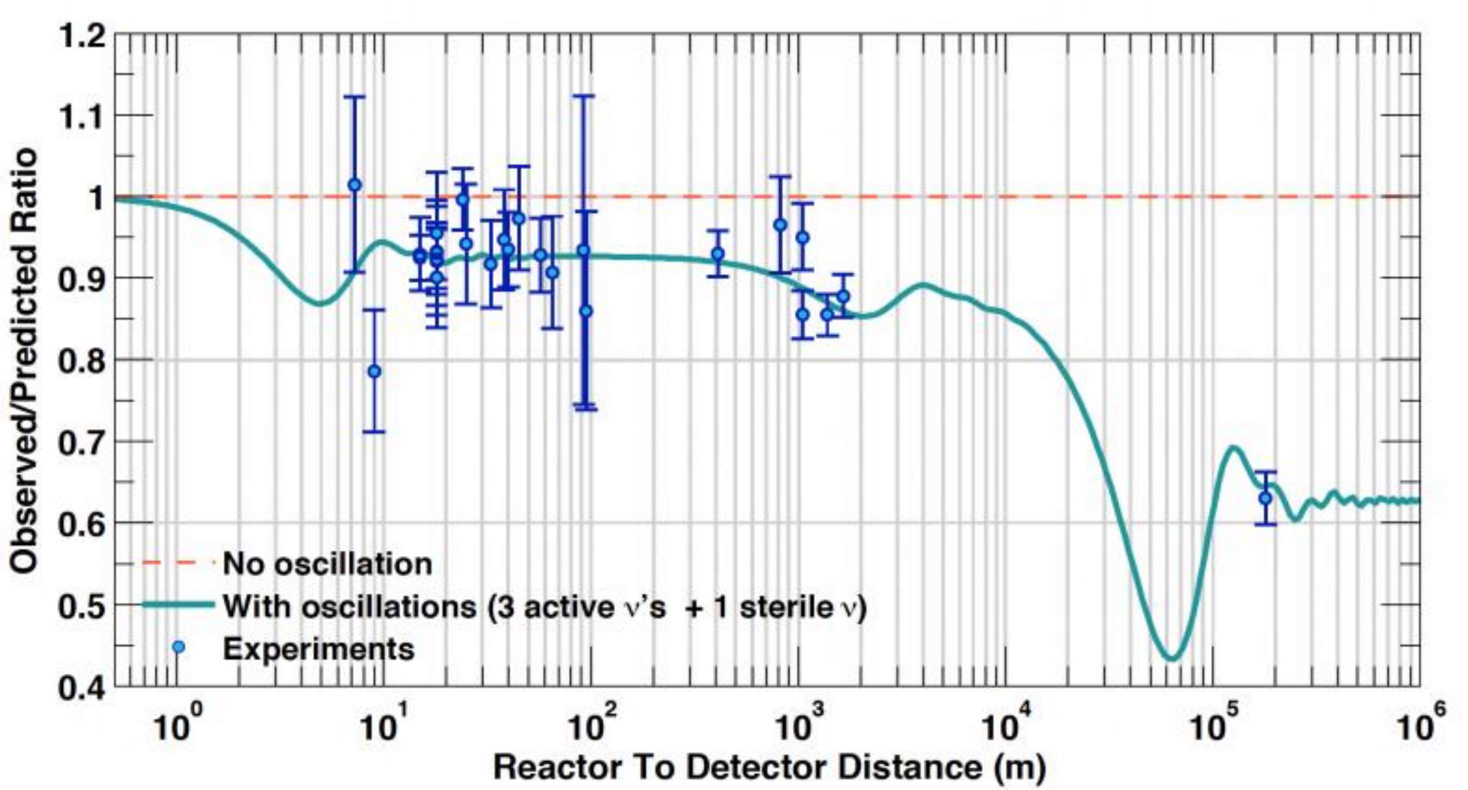


« Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment »

NEW NEUTRINO SEARCH

Reinterpretation of antineutrino detections by all reactor experiments with new uranium and plutonium spectra (CEA, France, 2011)

One point fits better with a new neutrino !



BLACK HOLES AT LHC

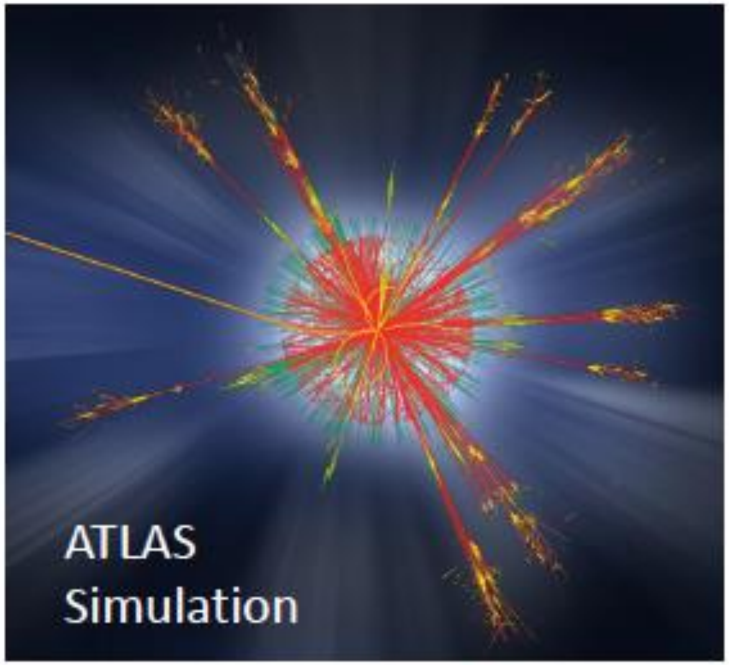
Gravitational interaction is negligible in particle physics, except if extra dimensions of space exist

Micro BH will decay in ~ 10^{-27} s

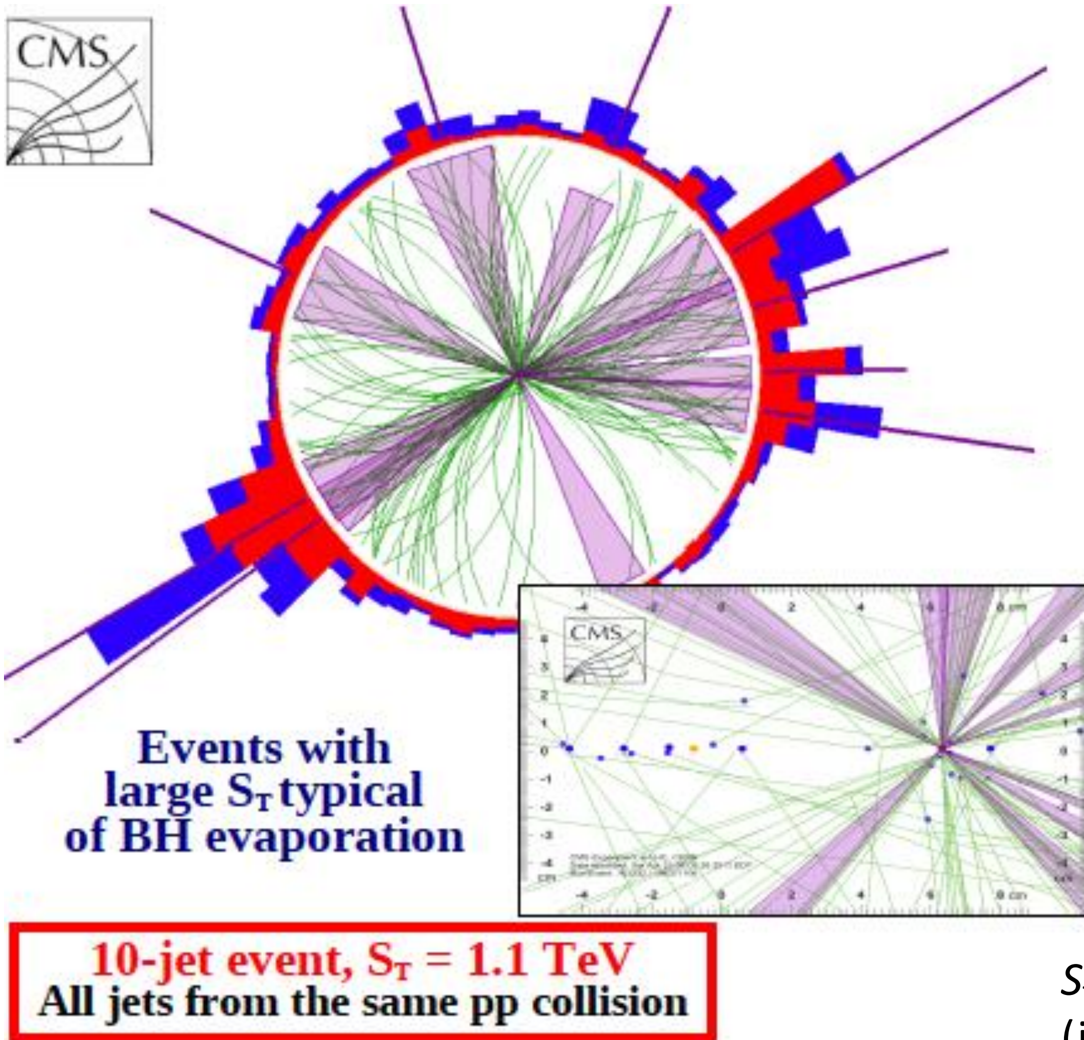
Absence of complete quantum theory of gravitation

Cross section calculation is semi classical : $\sigma = \pi R_S^2$

Analysis strategy :
M_{TH} threshold mass to eliminate QCD background
isotropy of the decay and particles democracy
high multiplicity of all types of high P_T jets



BLACK HOLES AT LHC



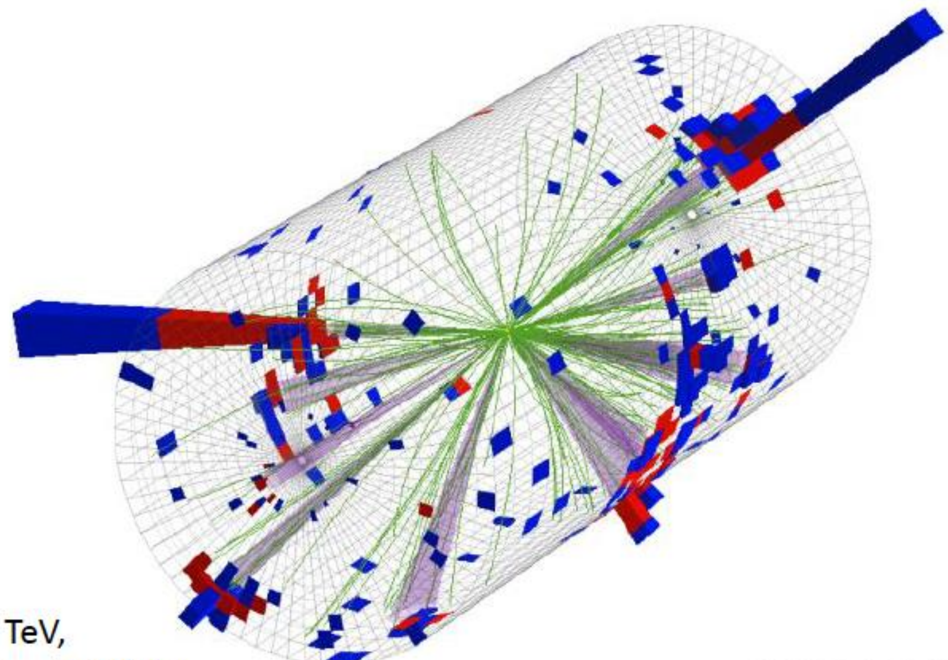
High multiplicity event

Good tracker quality
→ vertices from simultaneous interactions are well separated
many jets are reconstructed

S_T = scalar sum of E_T of objects (jets, electrons, muons, gammas)

BLACK HOLES AT LHC

Event candidates @ 13 TeV

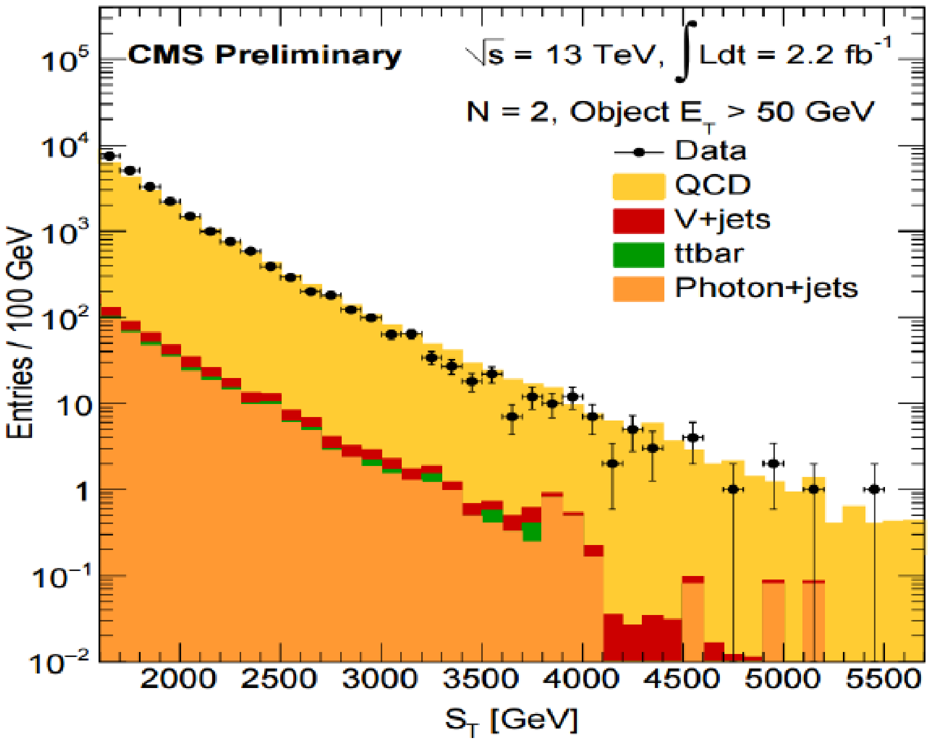


$$S_T = \sum_{i=1}^{N_{jet}} E_T$$

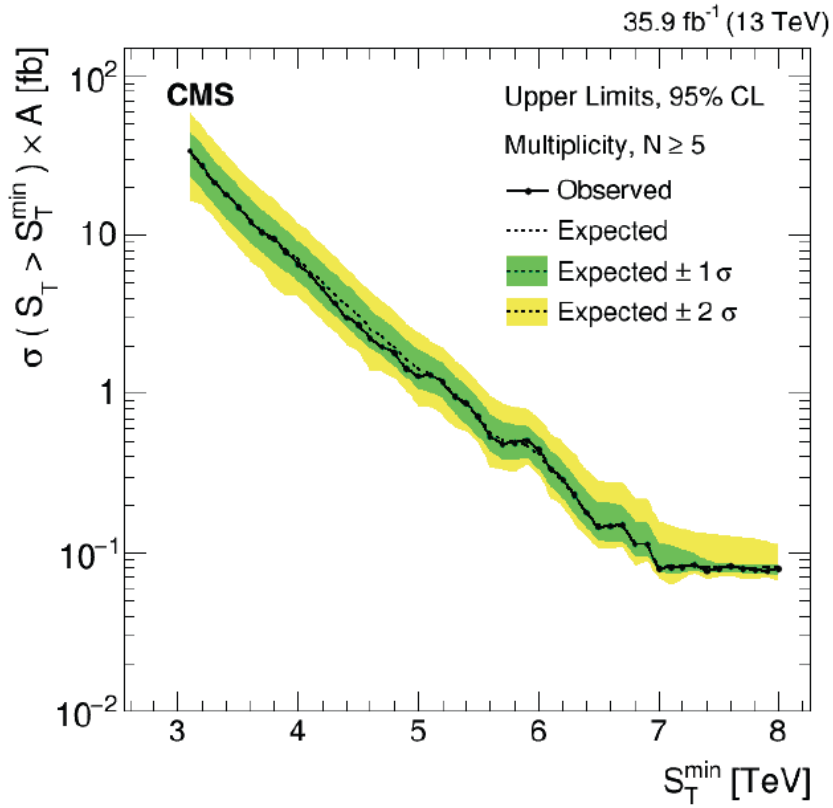
- 9 jets,
- S_T = 5.56 TeV,
- Missing E_T = 8.4 GeV,
- multiplicity N = 9

CMS Experiment at LHC, CERN
Data recorded: Wed Oct 21 06:04:21 2015 CEST
Run/Event: 259685 / 155512460

BLACK HOLES AT LHC



QCD backgroud



Model independent limit on cross-section

Limits are roughly 0.04 fb at high values of S_T

HEAVY PARTICLE at LHC

ATLAS and CMS detect measure the kinematical variables of all SM particles, except neutrinos.

The total energy is measured by calorimeters, except in the beam region.

A missing transverse energy E_T is the signature of a neutrino or some DM particles

Trigger is : at least one visible object (jet, lepton, photon)

Results are presented for 36 fb^{-1} collected in run 2 at 13 TeV

- SUSY models with conserved R-parity predict lightest SUSY particle (LSP) stable, electrically neutral, feebly interacting with SM

- simplified models : **mediator** particle

- invisible decays of 125 GeV Higgs boson

HEAVY PARTICLE at LHC

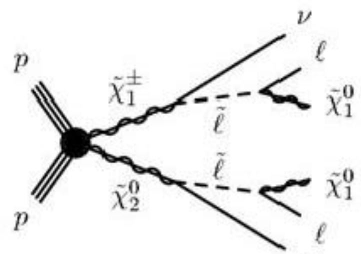
SUSY PARTICLE DECAYS

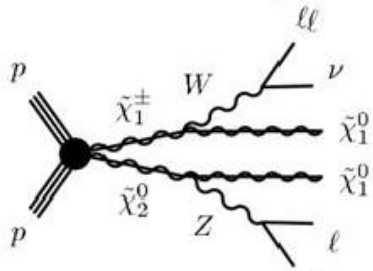
MET + X

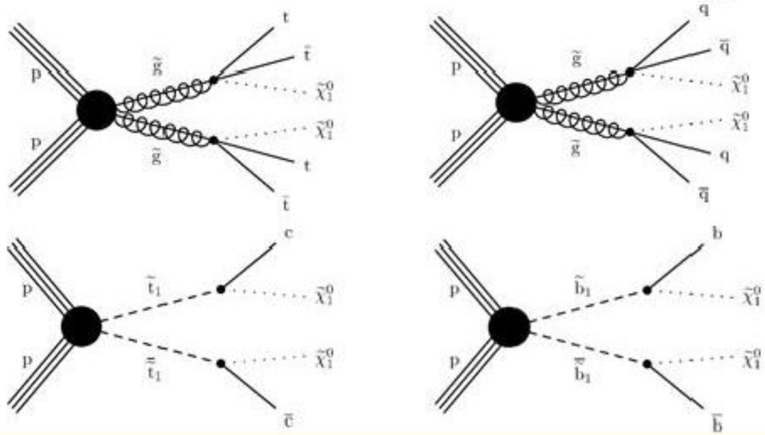
X=visible multi-object FS
- including one or more jets, W/Z(→jets),
- HF(b/t) pair(→b-jets),
- h(→b/τ jets),
- e, μ, τ-jet, γ

and/or

Long Lived Particles (LLP)



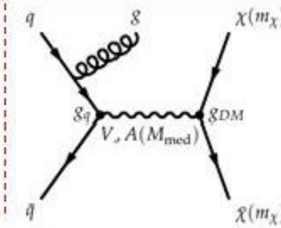




DIRECT PRODUCTION via NEW MEDIATORS

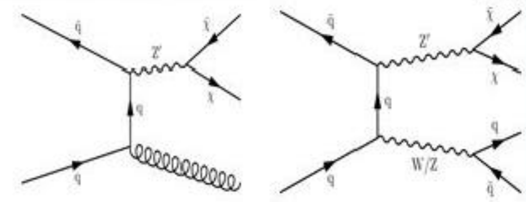
DM - SM coupling

Spin 1 (Vector or Axial-Vector) mediator

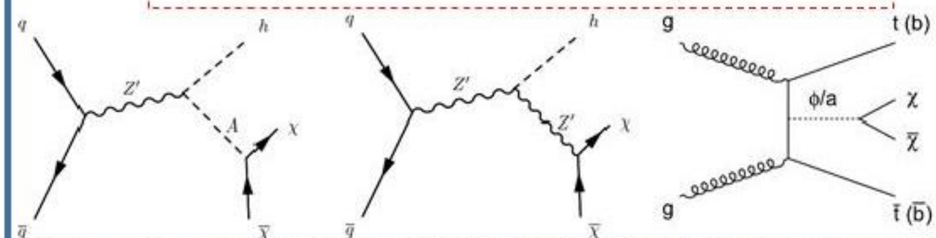


MET + X

X = jet, γ,
W/Z(→jets/ll),
h(→b/τ jets)
HF(b/t) pair(→b-jets)

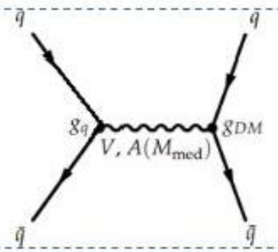


Spin 0 (Scalar or Pseudo-scalar) mediator



NEW MEDIATORS

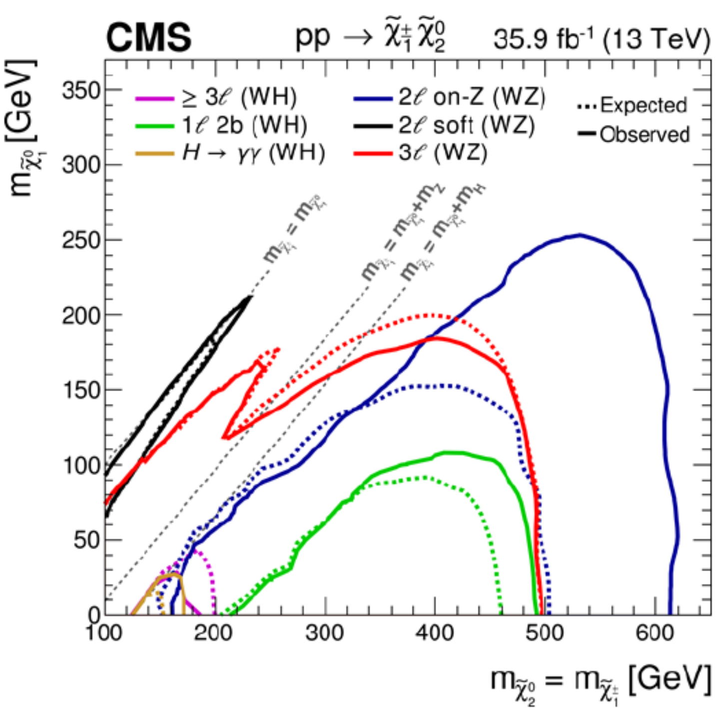
Coupling to SM fermions
RESONANCE SEARCHES
IN DIJET OR DILEPTON FINAL STATES



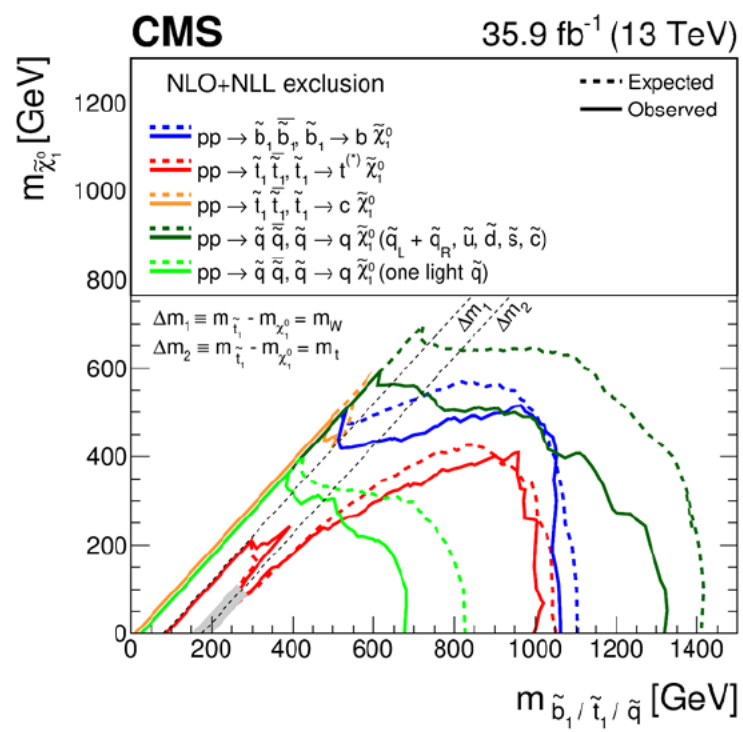
HEAVY PARTICLE at LHC

SUSY search : complete models but with many parameters

Results provided as cross-section limit for given process,
as a function of masses of the heaviest SUSY particle and the LSP SUSY particle



chargino and neutralino



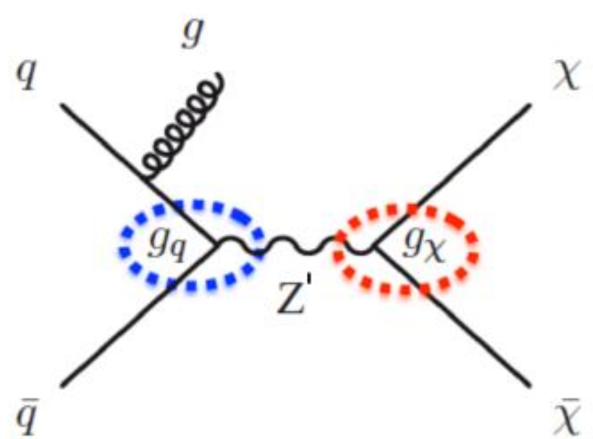
top, bottom, light flavour squark

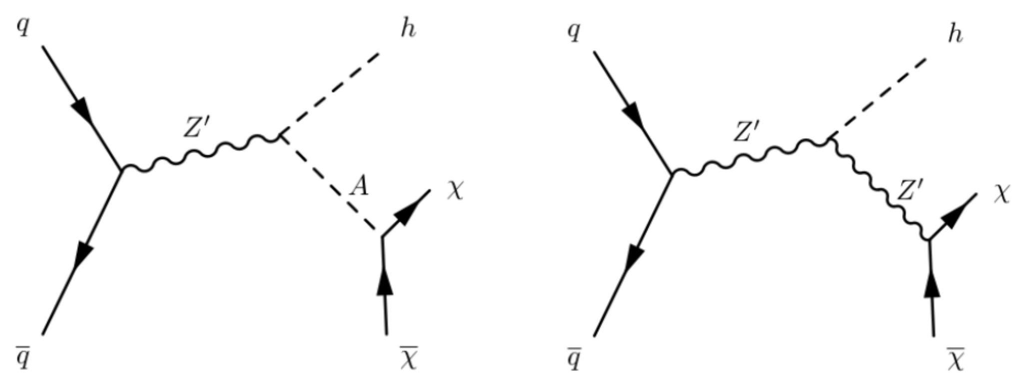
HEAVY PARTICLE at LHC

A more generic simplified model : the SM and DM interact through a new boson termed “mediator”

Only 4 parameters m_{med}, m_{DM}, g_q (coupling to quarks) and g_{DM} (coupling to DM)

Mediator can be spin1 (vector or axial vector) or spin 0 (scalar or pseudo scalar)



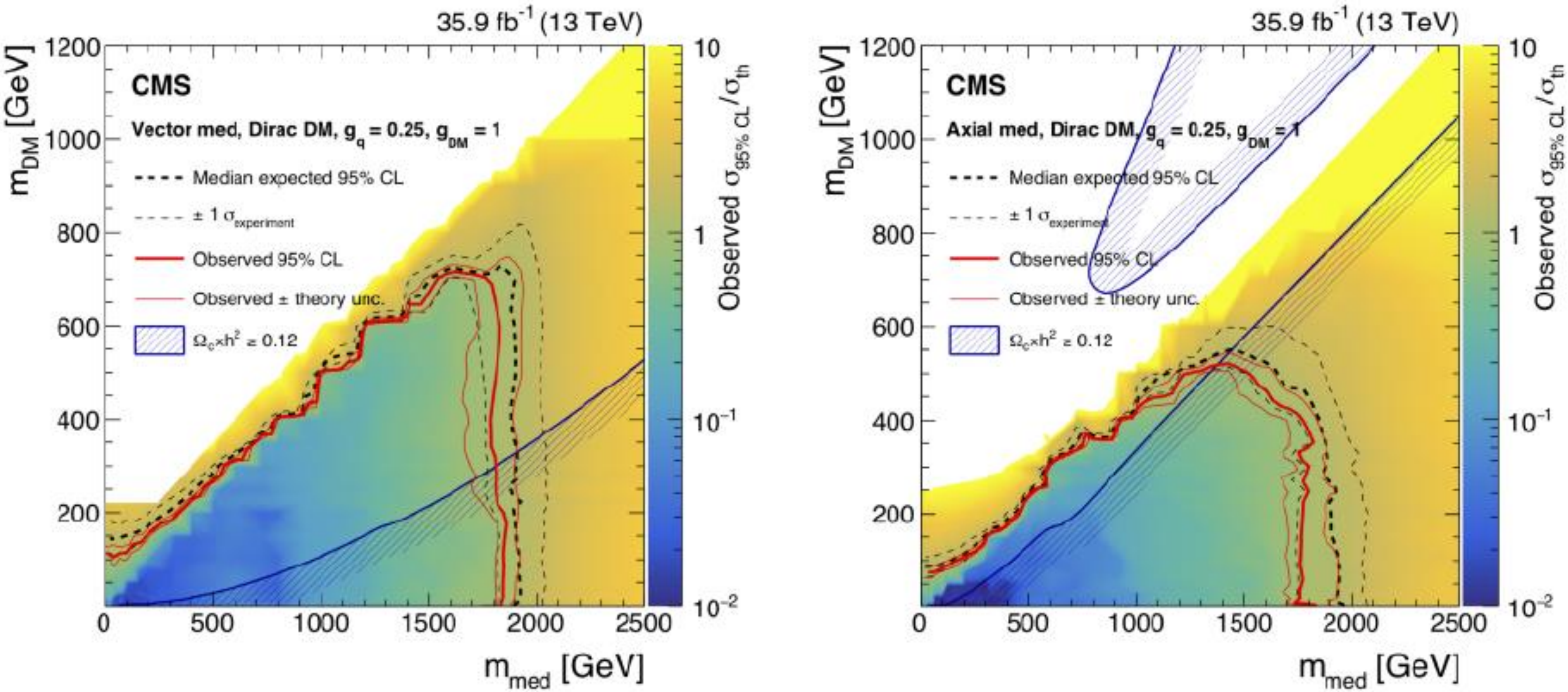


(a) Z′-2HDM (b) Z′-Baryonic

mono-jet, mono-Z, mono-γ

mono-Higgs

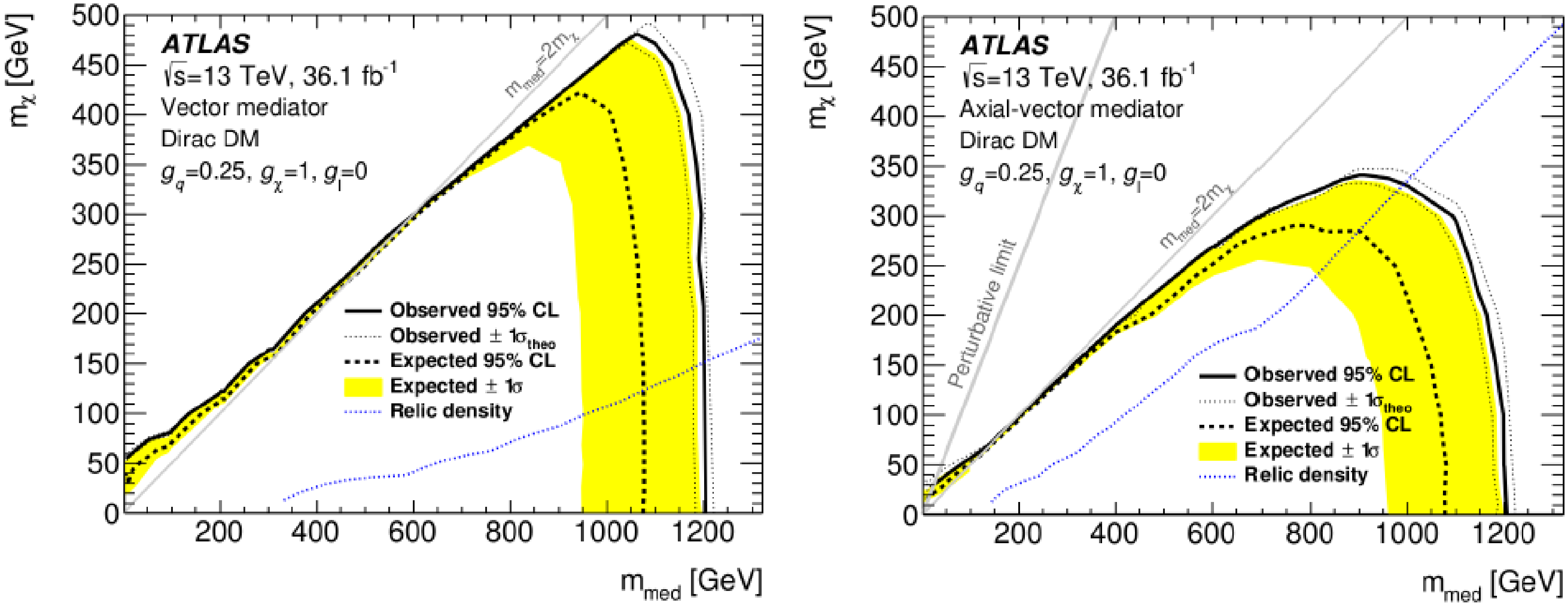
HEAVY PARTICLE at LHC



(a) CMS

CMS mono-jet

HEAVY PARTICLE at LHC

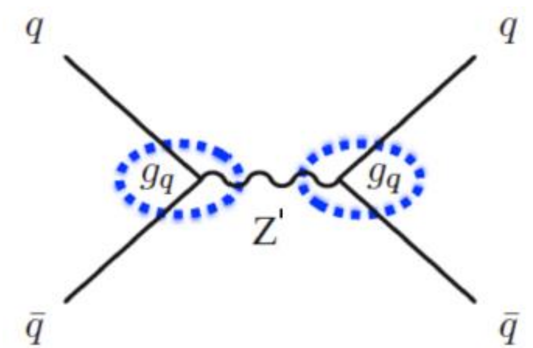


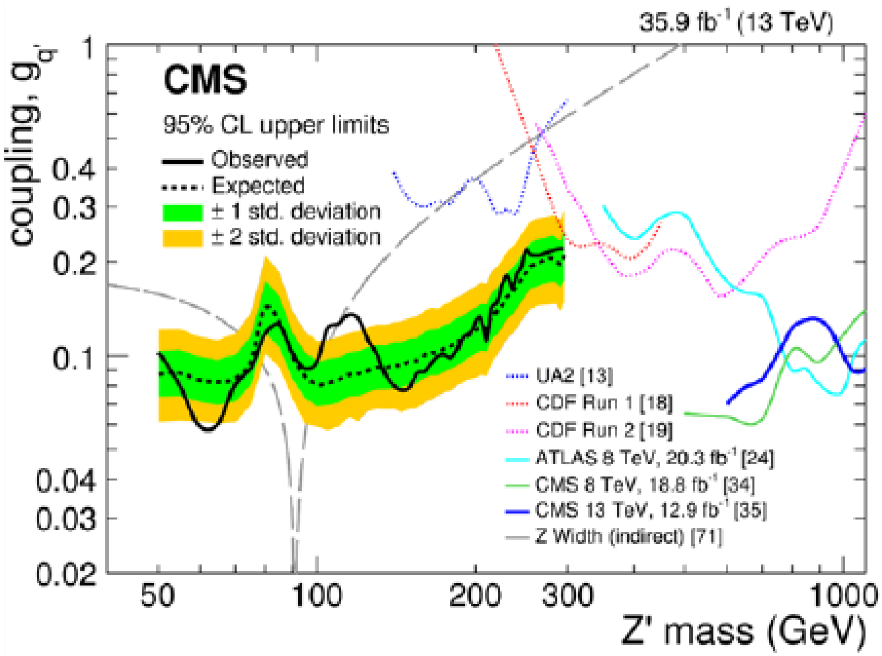
(b) ATLAS

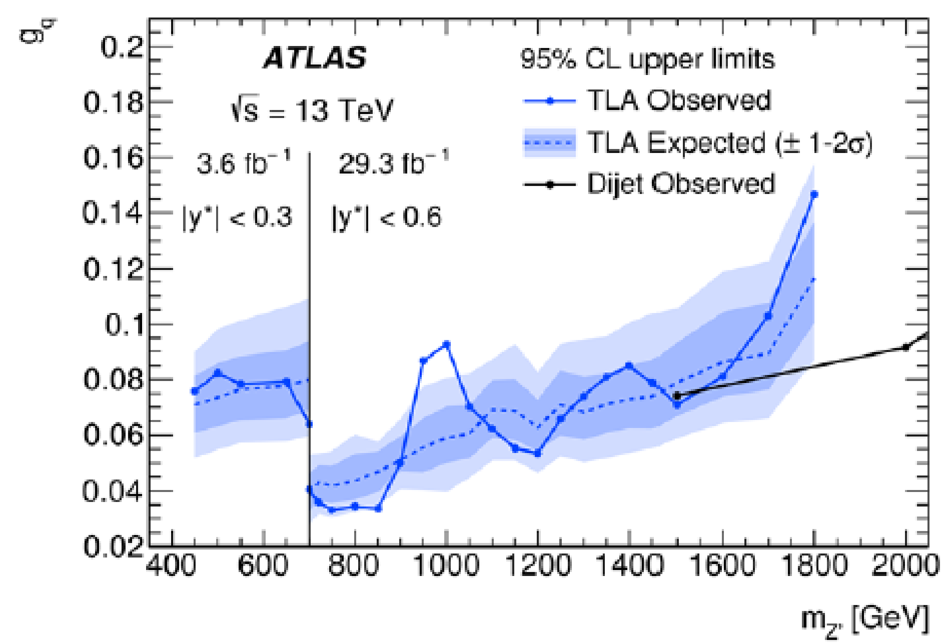
ATLAS mono-γ

HEAVY PARTICLE at LHC

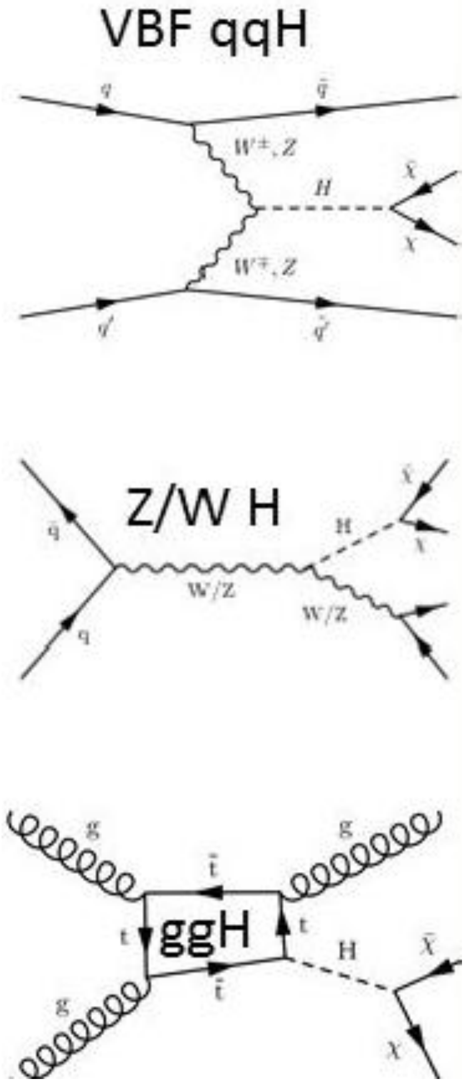
Mediator can also decay into fermions pair
as a resonance ≤ 1 TeV
undetected in previous search (Z', extra dimensions, etc)
because of weak coupling to SM
=> dedicated analysis of jet substructure



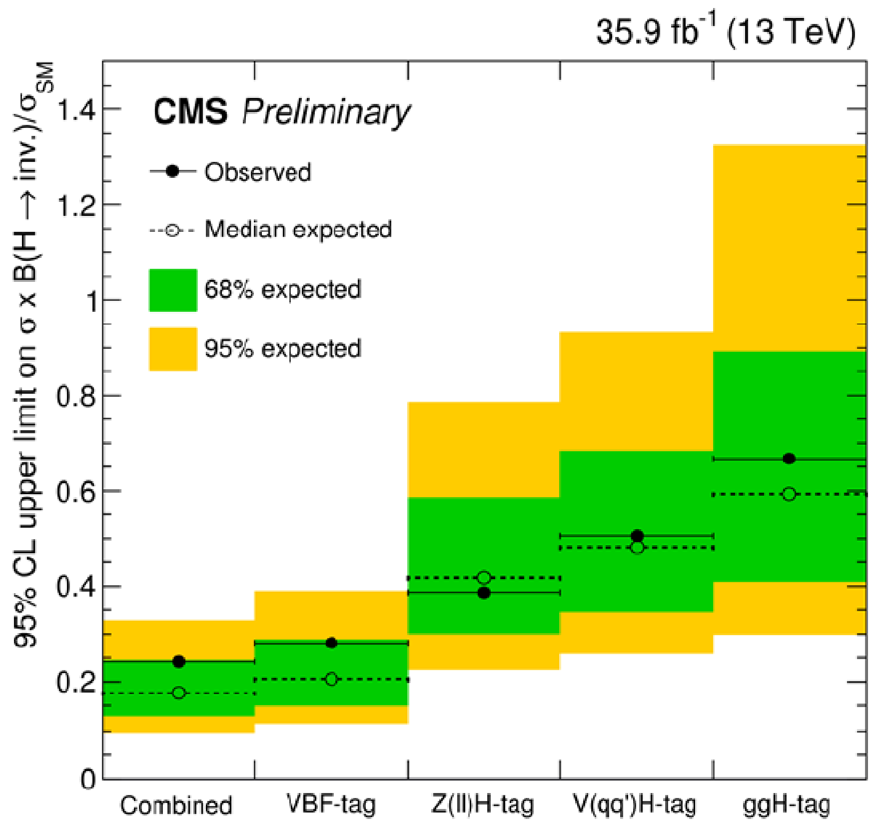




HEAVY PARTICLE at LHC



Higgs boson invisible decays :
H → ZZ → 4 neutrinos, branching ratio 0.1 %
May be largely enhanced by BSM scenarios
Search : qq → qqH , gg → H , qq → ZH



AXION

Instead of producing new particles in laboratory, detect **natural ones**

Many experiments built to detect solar axions with superconducting magnets

ADMX (U. Washington) microwave

CAST, CERN's axion solar telescope, moves on its rail to follow the Sun (Image: Max Brice/CERN)

CAST (CERN) X rays

COSMOLOGIC CONSTRAINTS

History of Universe constraints some properties of DM

DM must have a role in the **formation of structures** (large : galaxy clusters, galaxies) and small (gas clouds, stars) since DM is 5 times more abundant than matter

N-body simulations : best agreement with observations, suggest that DM particles were non relativistic and short mean free path: CDM (cold dark matter)

DM interaction with SM particles must have a **cross section** σ compatible with present DM density "relic density"

Early Universe: $T >> M_{DM}$ → equilibrium DM-SM

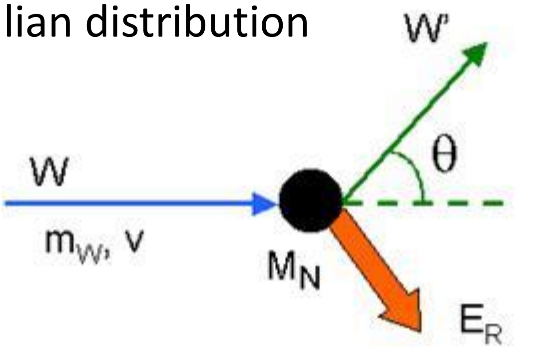
Present Universe: $T << M_{DM}$ → DM annihilation into SM, no DM creation
DM disappearance until mean free path in the Universe is large enough (decoupling)
→ $\sigma \approx$ weak interaction

COSMIC WIMP DIRECT DETECTION

Stable (τ > age of Universe), neutral, low σ, massive $M \approx$ 1 GeV to 100 TeV
Weak Interactive Massive Particle **WIMP**

Dark matter accumulates in the center of galaxies
Evaluated density 0.39 GeV/cm^3 , speed 220 km/s Maxwellian distribution

Elastic scattering on the matter nucleus of a detector
Isotropic or forward peaked (massive nucleus)



Unknown : **mass** and **cross section**

$E_R \approx$ 10 – 100 keV for $m_W \approx$ 10 GeV – 10 TeV

MSSM → 1 evt.day^{-1}.kg^{-1} much lower than usual radioactive background

Limitations : detector sensitivity at low m_W , WIMP flux at high m_W

Signatures : day and annual effect of Earth rotation and speed around Sun

COSMIC WIMP DIRECT DETECTION

Natural activity of human body is 10 000 Becquerel (1 bq = 1 decay/s)
Cosmic muons at sea level are ≈ 100 per second in 1 m^2

Experiments are shielded from cosmic muons by installation in mines
(Homestake and Soudan in USA, Sudbury SNOLAB in Canada, Kamiokande in Japan)
or tunnels under mountains (Modane in France, Gran Sasso in Italy, Jin Pin in China)

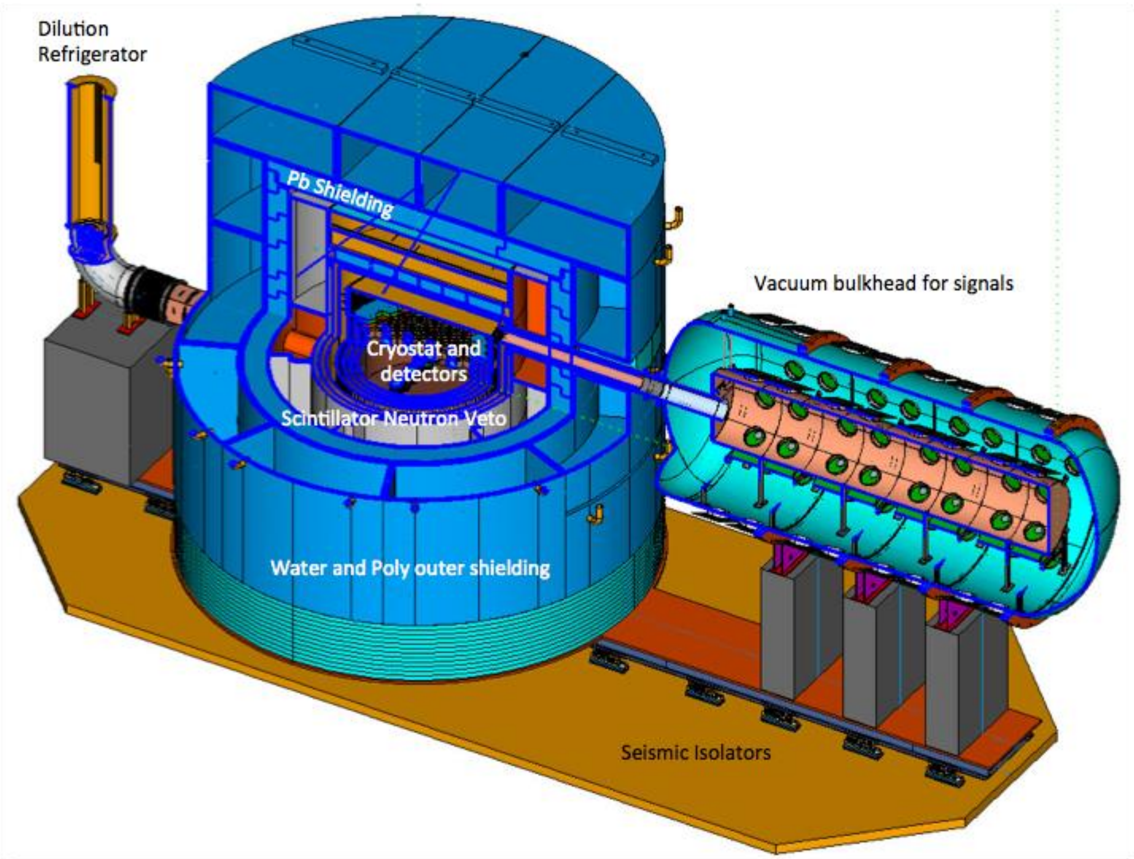
To reduce the background, several concentric shielding :
- polyethylene for neutrons
- lead for gammas (low radioactive lead from sunk Roman ships)
- scintillation counters to veto residual muons

High purity materials are mandatory to avoid contamination :
semi-conductor crystals (Ge, Si) or noble gas (Argon, Xenon)

E_R measured by temperature increase, ionisation and/or scintillation

COSMIC WIMP DIRECT DETECTION

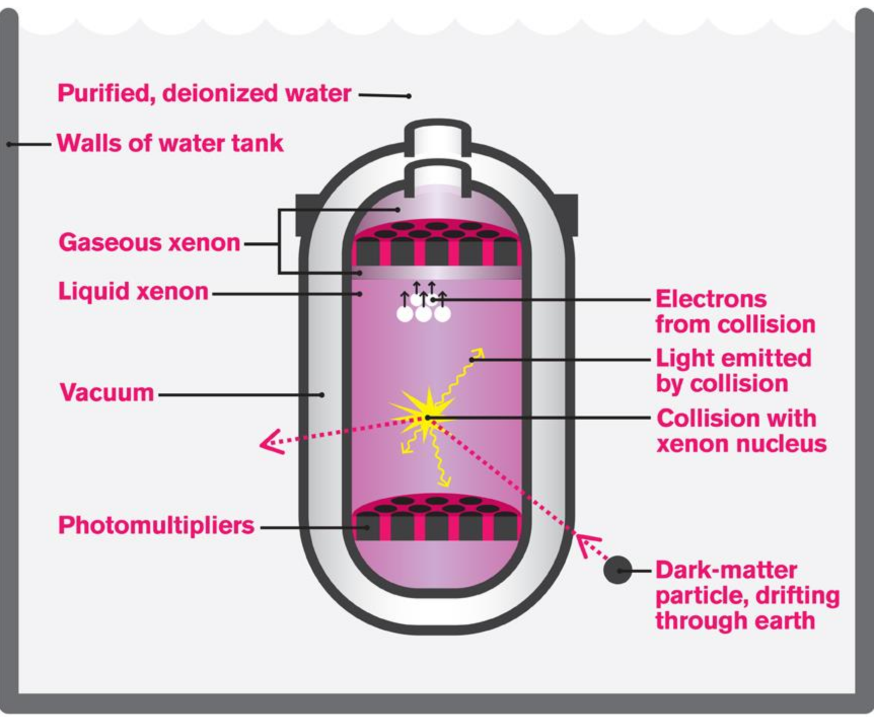
EDELWEISS (Modane)



SuperCDMS (SNOLAB)

In Ge or Si crystals at low temperature (few mK), vibration energy (heat) is quantified giving phonons which are detected, together with ionisation/scintillation

COSMIC WIMP DIRECT DETECTION



LUX (Homestake)

Xenon 1T (Gran Sasso)

Ar is cheap (1 % of air) Xe is expensive and heavier (9×10^{-8} of air), noble gas are easy to purify

Measure of scintillation and ionisation by drifting electrons in the gas phase
Scintillation/Ionisation ratio distinguish DM recoil against electrons

COSMIC WIMP DIRECT DETECTION

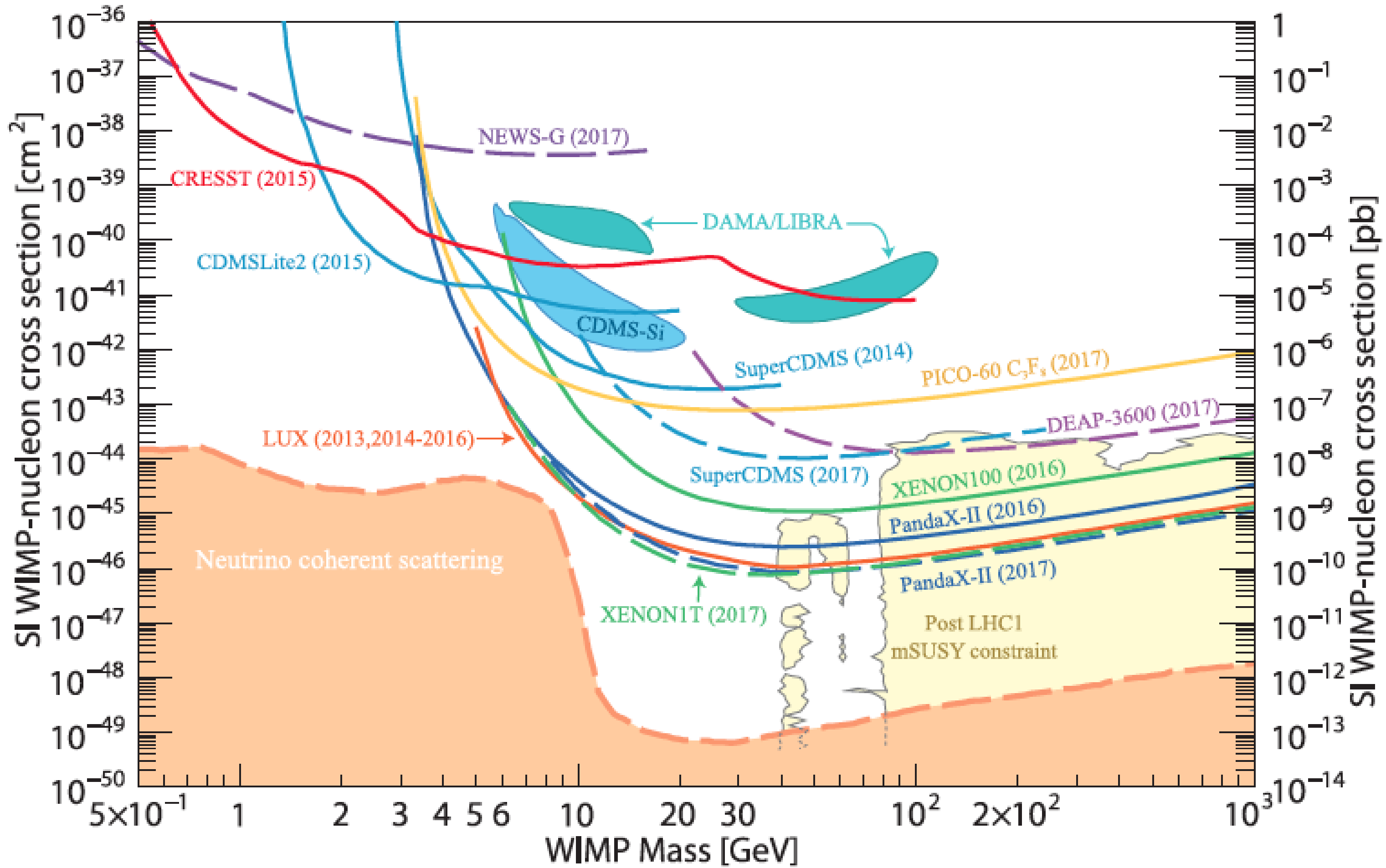
	Target	Fiducial Mass [kg]	Cross section [pb]	WIMP mass [GeV]
Spin independent high mass (>10 GeV)				
Xenon1t	Xe	1042	7.7×10^{-11}	35
PANDAX II	Xe	364	8.6×10^{-11}	40
LUX	Xe	118	1.1×10^{-10}	50
SuperCDMS	Ge	12	1.0×10^{-8}	46
DEAP	Ar	2000	1.2×10^{-8}	100
Spin independent low mass (<10 GeV)				
LUX	Xe	118	2×10^{-9}	10
Xenon1t	Xe	1042	2×10^{-9}	10
PANDAX II	Xe	364	2×10^{-9}	10
PICO60	C_3F_8 - F	46	2×10^{-7}	10
SuperCDMS	Ge HV	0.6	3×10^{-5}	3
CRESST	$CaWO_4$ - O	0.25	1×10^{-2}	1
NEWS-G	Ne	0.3	6×10^{-2}	1
Spin dependent p				
PICO60	C_3F_8 - F	54	3.4×10^{-5}	30

PICO60
bubble chamber

NEWS-G
gaseous Ne detector
specific for low-mass
WIMP

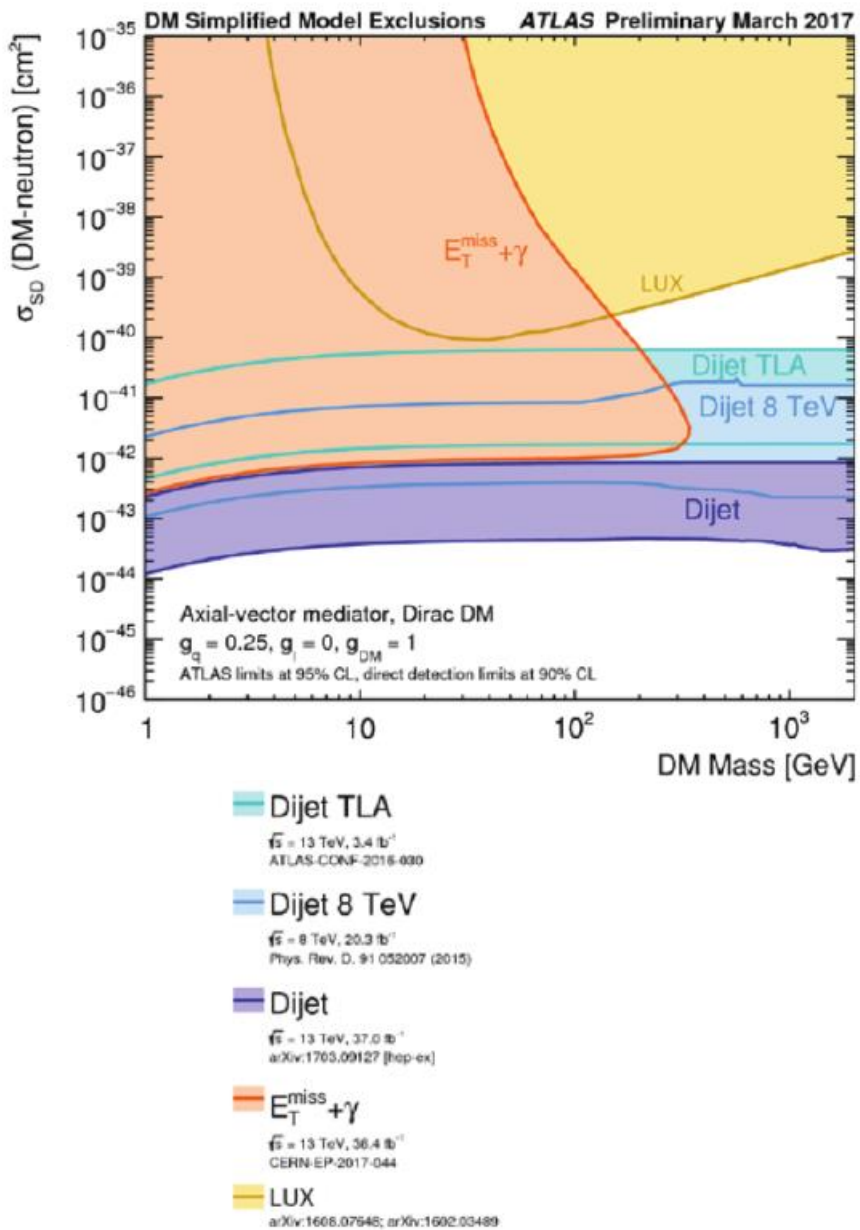
crystal mK experiments
are also designed
to detect **axions**
EDELWEISS

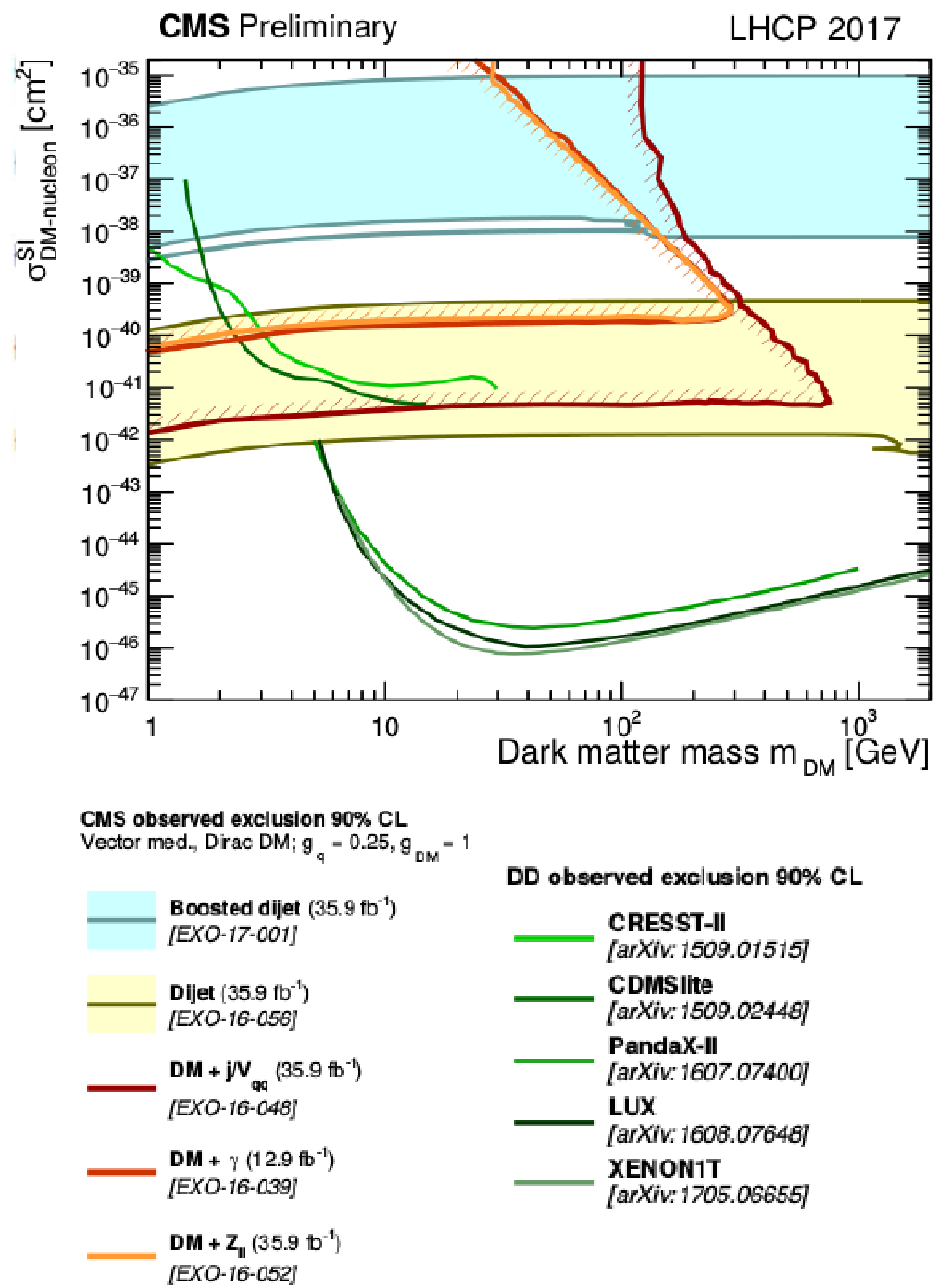
COSMIC WIMP DIRECT DETECTION



positive DAMA result is controversial

aim : reach the “neutrino floor”

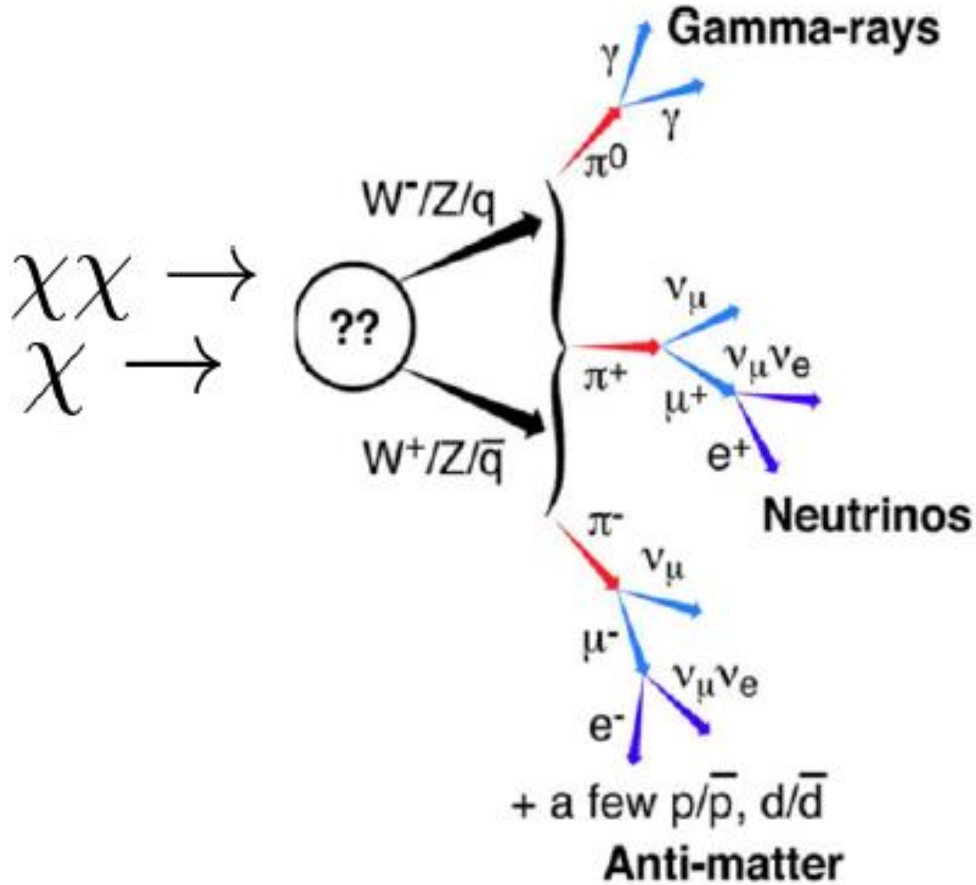

DM Simplified Model Exclusions
ATLAS Preliminary March 2017
σ_SD (DM-neutron) [cm²]
E_T^miss+γ
LUX
Dijet TLA
Dijet 8 TeV
Dijet
Axial-vector mediator, Dirac DM
g_q = 0.25, g_l = 0, g_DM = 1
ATLAS limits at 95% CL, direct detection limits at 90% CL
DM Mass [GeV]
Dijet TLA
√s = 13 TeV, 3.4 fb⁻¹
ATLAS-CONF-2016-030
Dijet 8 TeV
√s = 8 TeV, 20.3 fb⁻¹
Phys. Rev. D. 91 052007 (2015)
Dijet
√s = 13 TeV, 37.0 fb⁻¹
arXiv:1703.09127 [hep-ex]
E_T^miss+γ
√s = 13 TeV, 36.4 fb⁻¹
CERN-EP-2017-044
LUX
arXiv:1608.07648; arXiv:1602.03489


CMS Preliminary
LHCP 2017
σ^SI_DM-nucleon [cm²]
Dark matter mass m_DM [GeV]
CMS observed exclusion 90% CL
Vector med., Dirac DM; g_q = 0.25, g_DM = 1
Boosted dijet (35.9 fb⁻¹)
[EXO-17-001]
Dijet (35.9 fb⁻¹)
[EXO-16-056]
DM + j/V_qq (35.9 fb⁻¹)
[EXO-16-048]
DM + γ (12.9 fb⁻¹)
[EXO-16-039]
DM + Z_ll (35.9 fb⁻¹)
[EXO-16-052]
DD observed exclusion 90% CL
CRESST-II
[arXiv:1509.01515]
CDMSlite
[arXiv:1509.02448]
PandaX-II
[arXiv:1607.07400]
LUX
[arXiv:1608.07648]
XENON1T
[arXiv:1705.06655]

WIMP INDIRECT DETECTION

If one does not detect WIMP on the Earth,

one can try to detect the result of WIMP self-annihilation or decay somewhere in the Universe



Background : many astrophysical mechanisms can produce gammas, neutrinos, or charged antiparticles

WIMP INDIRECT DETECTION

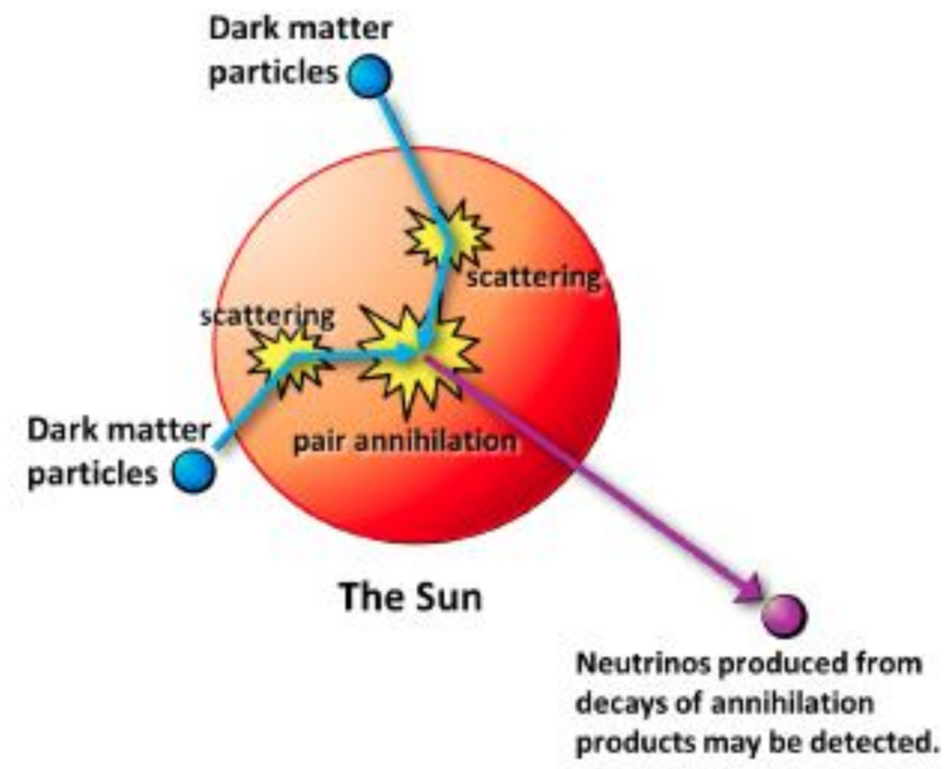
DM is sensitive mainly to gravitation,
it accumulates in the centre of Sun or Earth

The direction is a good signal of the origin

Neutrinos are detected by interaction in large volume of water or ice

Gammas in space or on ground

Antiparticles in space



Credit: www-sk.icrr.u-tokyo.ac.jp

WIMP INDIRECT DETECTION

Neutrino detection in 50 000 tons of water SuperKamiokande (Japan)

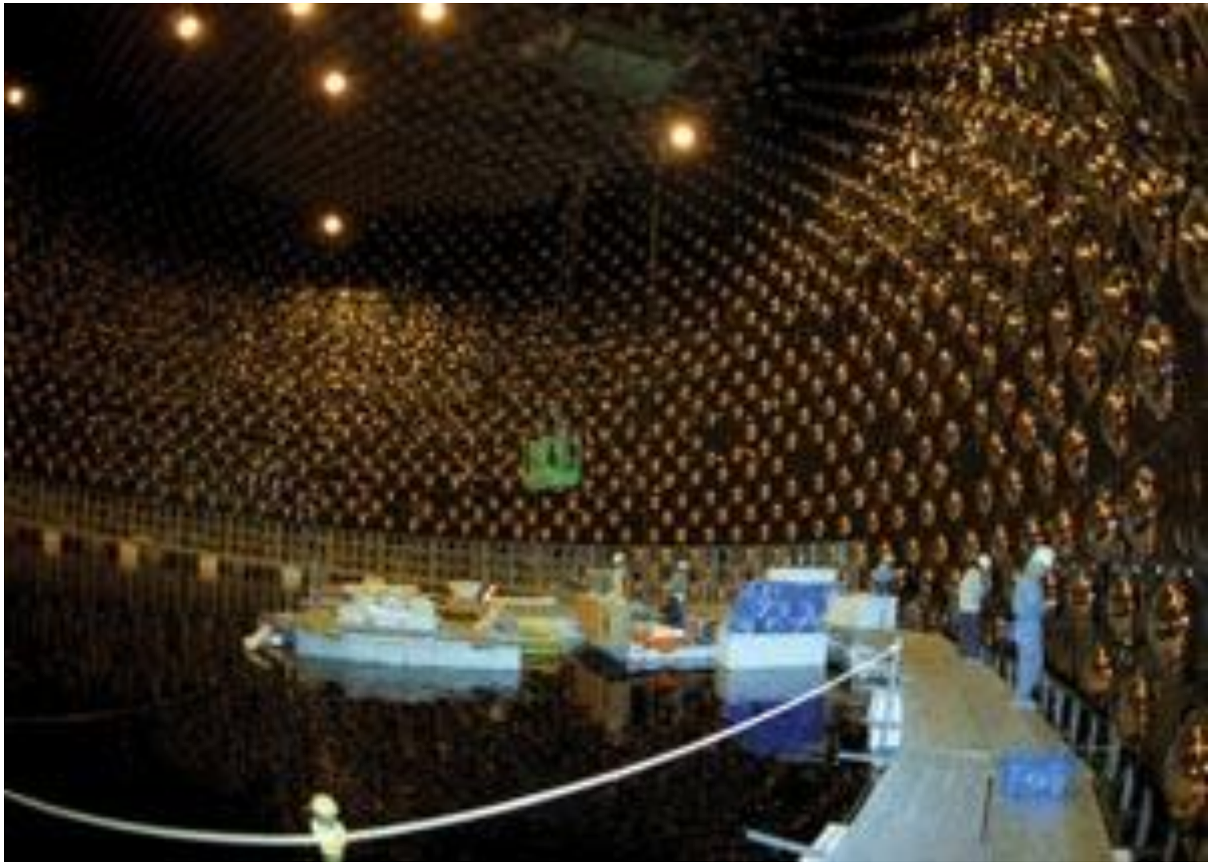
Electron or muon give
Cerenkov light :
energy and direction

ν_μ from accelerator
at 295 km distance

Detection of atmospheric ν_μ
decays of charged cosmic rays

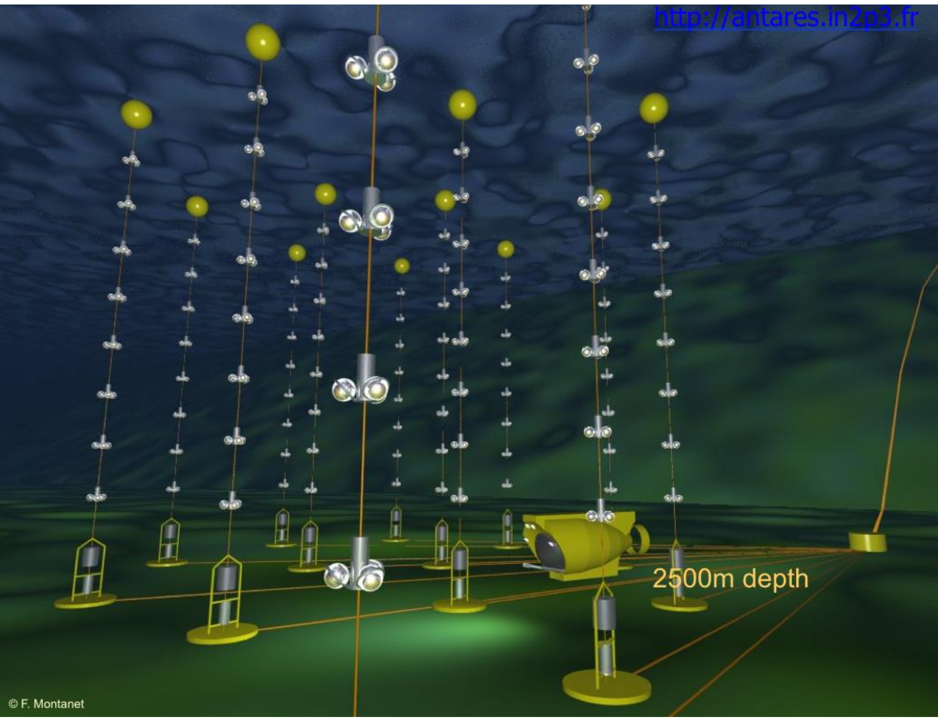
High energetic ν_μ from DM ?

Low DM mass ≈ 50 GeV

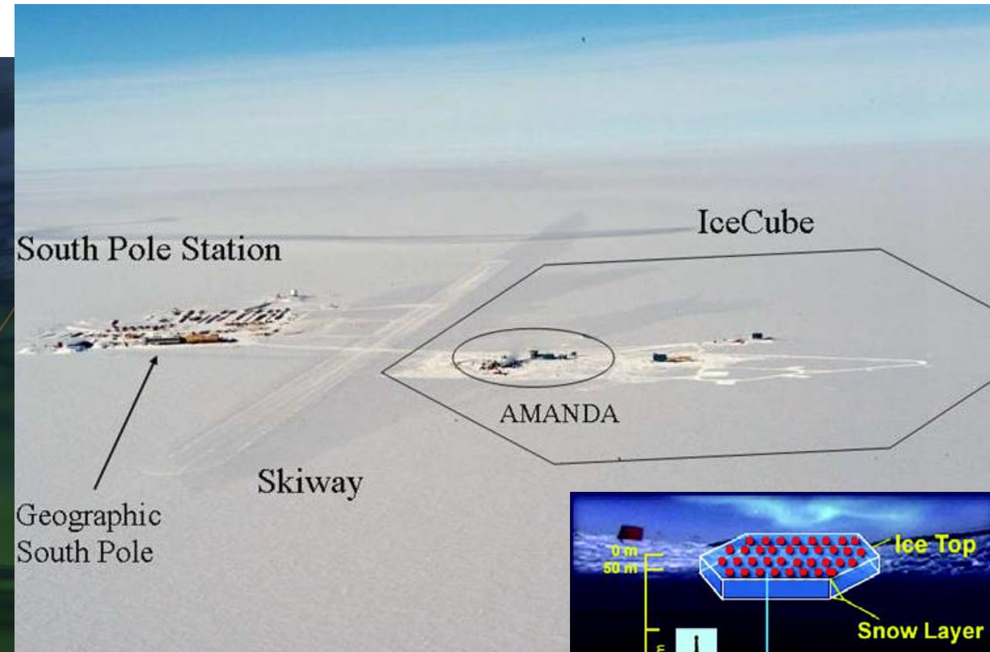


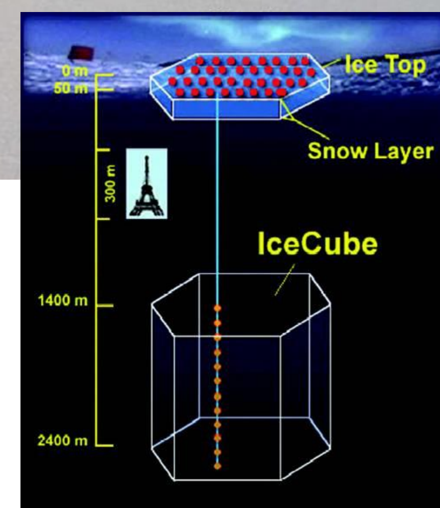
WIMP INDIRECT DETECTION

Water : Mediterranean sea
ANTARES, KM3NeT



Ice : South pole





AMANDA,
Ice Cube (1 km^3)

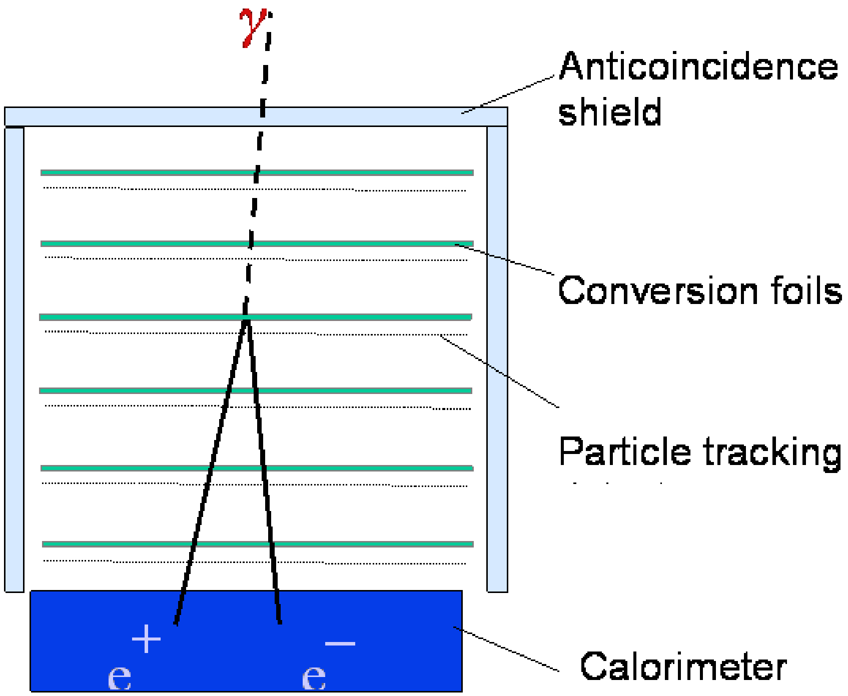
Larger volume, more spaced photomultipliers
=> higher WIMP mass > 50 GeV

WIMP INDIRECT DETECTION

Gamma detectors

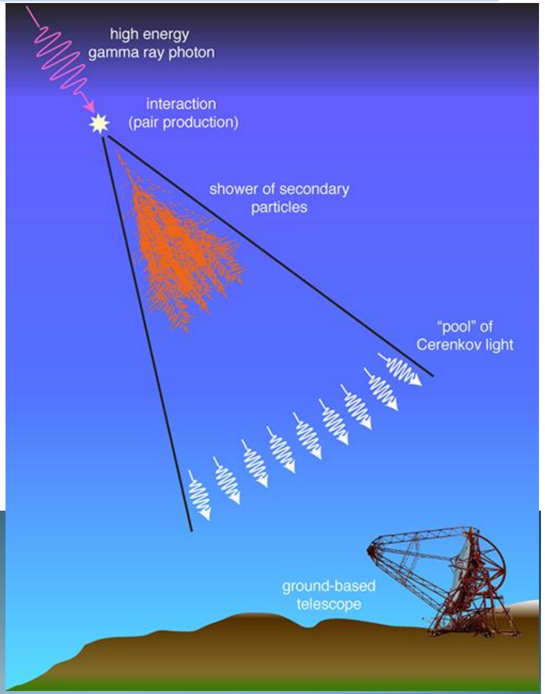
FERMI satellite

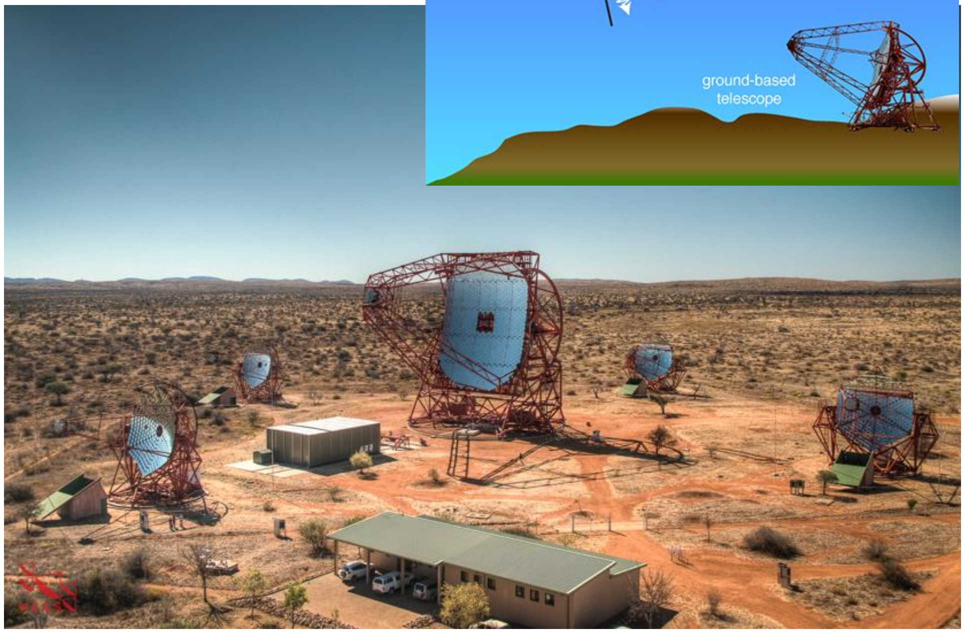
0.1 – 10 GeV



HESS
Cerenkov detector
Namibia

0.1 – 100 TeV

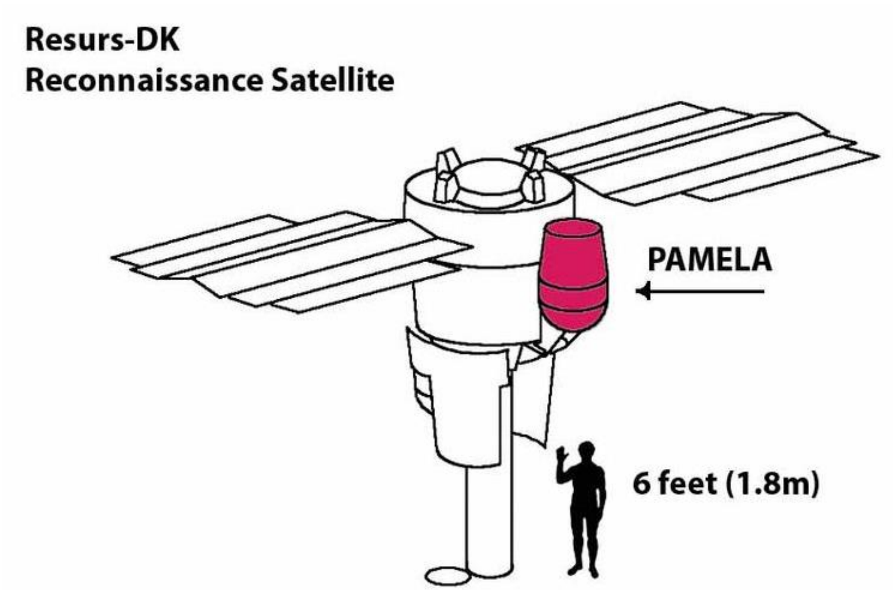




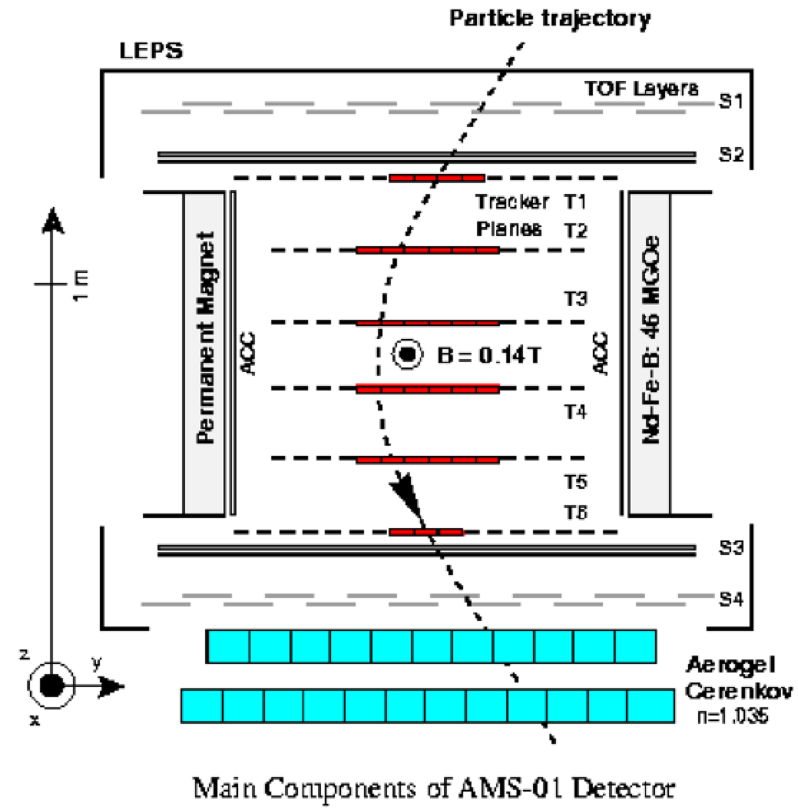
WIMP INDIRECT DETECTION

Detection of **antimatter** from space by satellites

Tracking of e^+, antiproton, antinuclei with permanent magnet



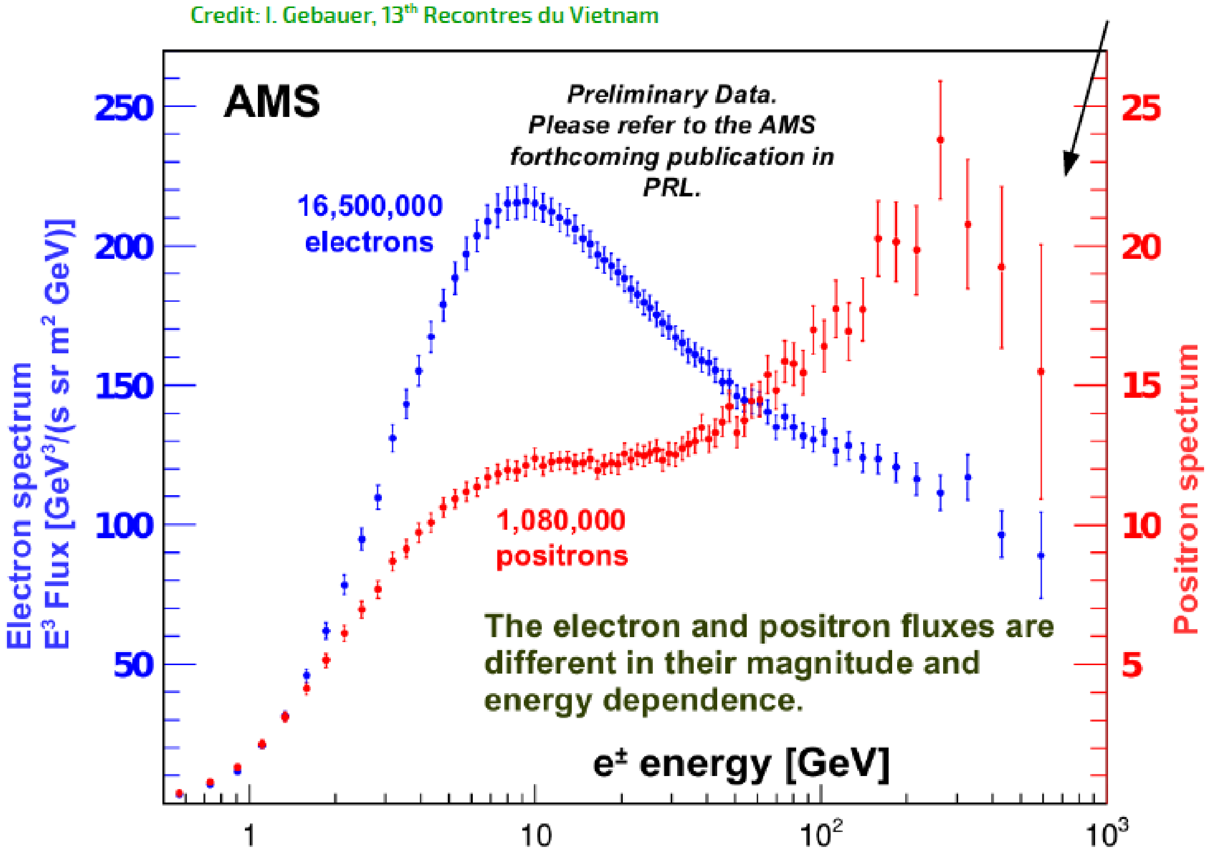
PAMELA mission



AMS in ISS

WIMP INDIRECT DETECTION

Credit: I. Gebauer, 13th Recontres du Vietnam



The positron excess, also seen by PAMELA, cannot be due only to DM, because no signal is seen in gamma and antiproton

a possibly detectable antideuteron could be a good signal of DM

IF DARK MATTER DOES NOT EXIST

MOND : MOdified Newtonian Dynamics proposed in 1983 by Milgrom

Acceleration of gravitation a is smaller than $1 / r^2$ law for low value of a

$$\frac{G\,M}{r^2} = a$$ is replaced by $$\frac{G\,M}{r^2} = a\,\mu\left(\frac{a}{a_0}\right)$$

$\mu \rightarrow 1$ when $a >> a_0$ in the Solar system $\mu \rightarrow \frac{a}{a_0}$ when $a << a_0$

The empirical choice $a_0 = 1.2 \times 10^{-10}$ m s^{-2} to fit galaxy rotation

Relativistic versions exist

To compete with Λ-CDM model, MOND has to agree with data : gravitational lenses, galaxy clusters, Planck precise data, new results on gravitational waves

Combining MOND and a small amount of hot DM by neutrinos is a possibility

IF DARK MATTER DOES NOT EXIST

Theory of Dirac-Milne Universe (Chardin)

Instead of modifying Newton law, modify the equivalence principle
(gravitational mass = inertial mass)

Antimatter has a **negative** gravitational mass, its inertial mass is positive

This Universe contains as much antimatter than matter
the antimatter is repulsive, so it is diffuse and separated from matter

Need to fit astrophysical data

Direct test : 3 experiments in progress to measure the effectof the Earth gravitational field on **antihydrogen** atoms at CERN
Gbar, AEgIS, ALPHAg

CONCLUSION

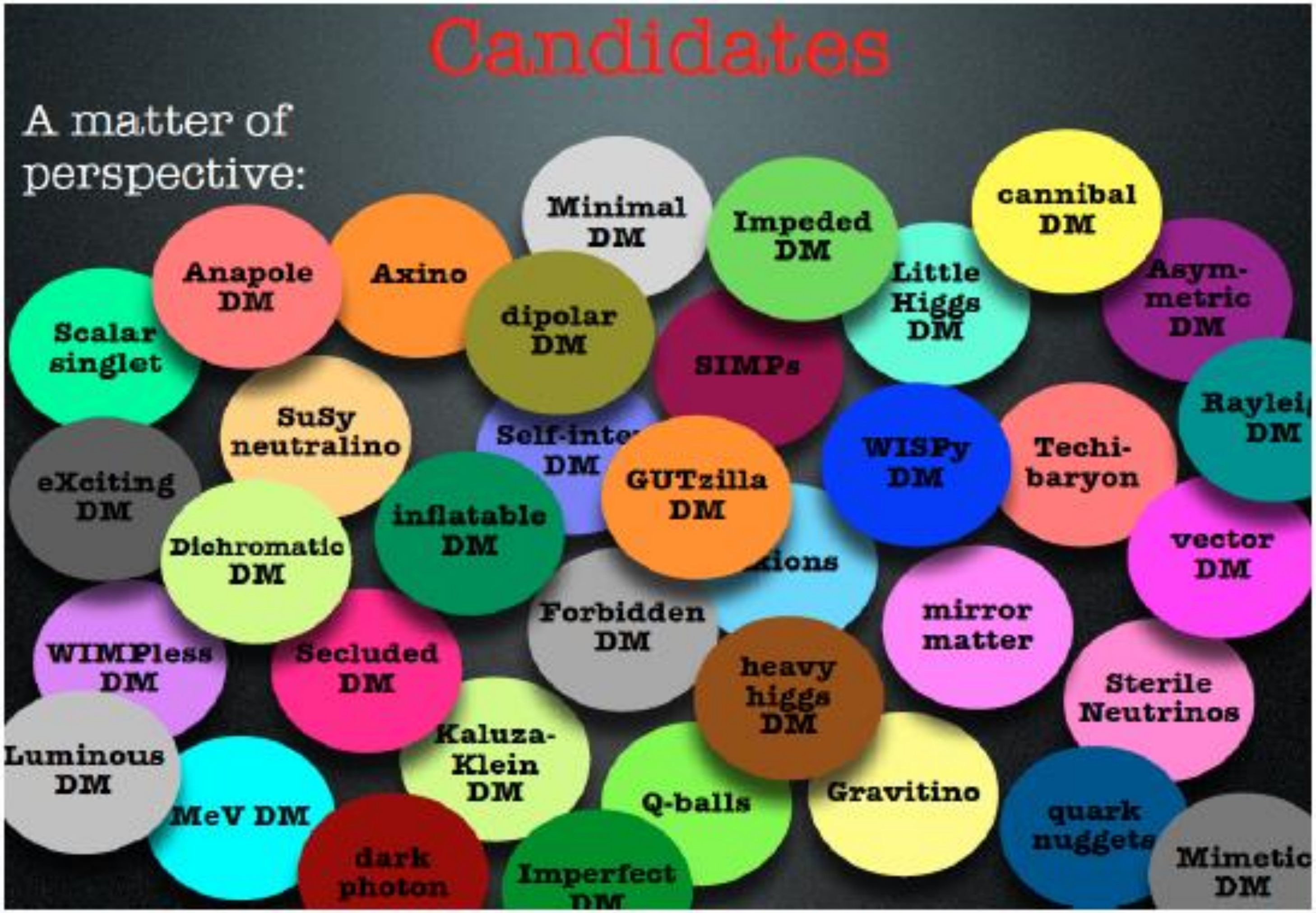
The Λ-CDM model is the most precise tool ever found for understanding the Universe **BUT** the dark matter has not been detected yet in particle physics, despite experiments everywhere at accelerators, underground, undersea or in space

New developments are still in progress to increase the sensibility, and beat the backgrounds

If we succeed to find dark matter particles, a new era is open in particle physics

If not, gravitation theory, as known since Newton and Einstein, must be amended, that would be another revolution in physics

EXTRA SLIDE

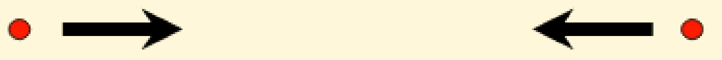


Marco Cirelli, JMS 2016, http://www.apc.univ-paris7.fr/APC/Conferences/jmsfrance2016/slides/Cirelli.DMthDD.APC.pdf

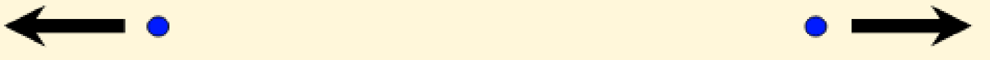
EXTRA SLIDE

Negative mass in GTR (Bondi) ?

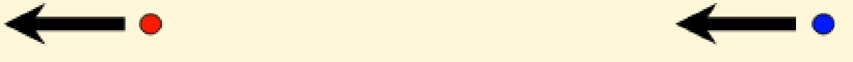
Two positive masses attract each other



Two negative masses repulse each other



One positive mass and one negative mass : runaway



● Positive mass particle
● Negative mass particle