Astroparticle Physics – the Dark Side of the Universe

Claudia Wulz and Wolfgang Waltenberger
Institute of High Energy Physics, Vienna
TU Vienna, CERN, Geneva

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The Dark Side of the Universe

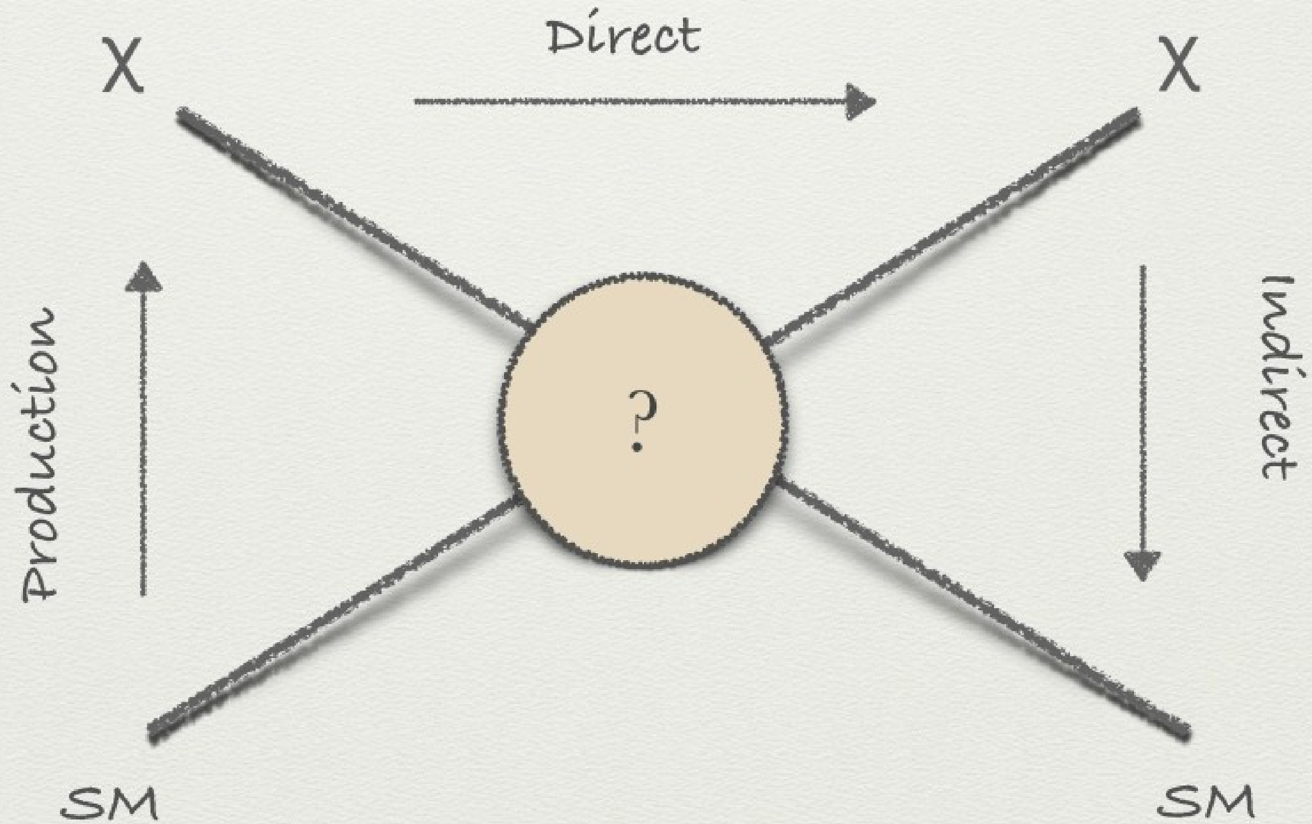
Dark Matter

- Evidence for dark matter
- Theory of dark matter
- Searches for dark matter
  - Searches at colliders
  - Direct searches
  - Indirect searches

Dark Energy and the
History and Fate of the Universe

(3) Searches for Dark Matter

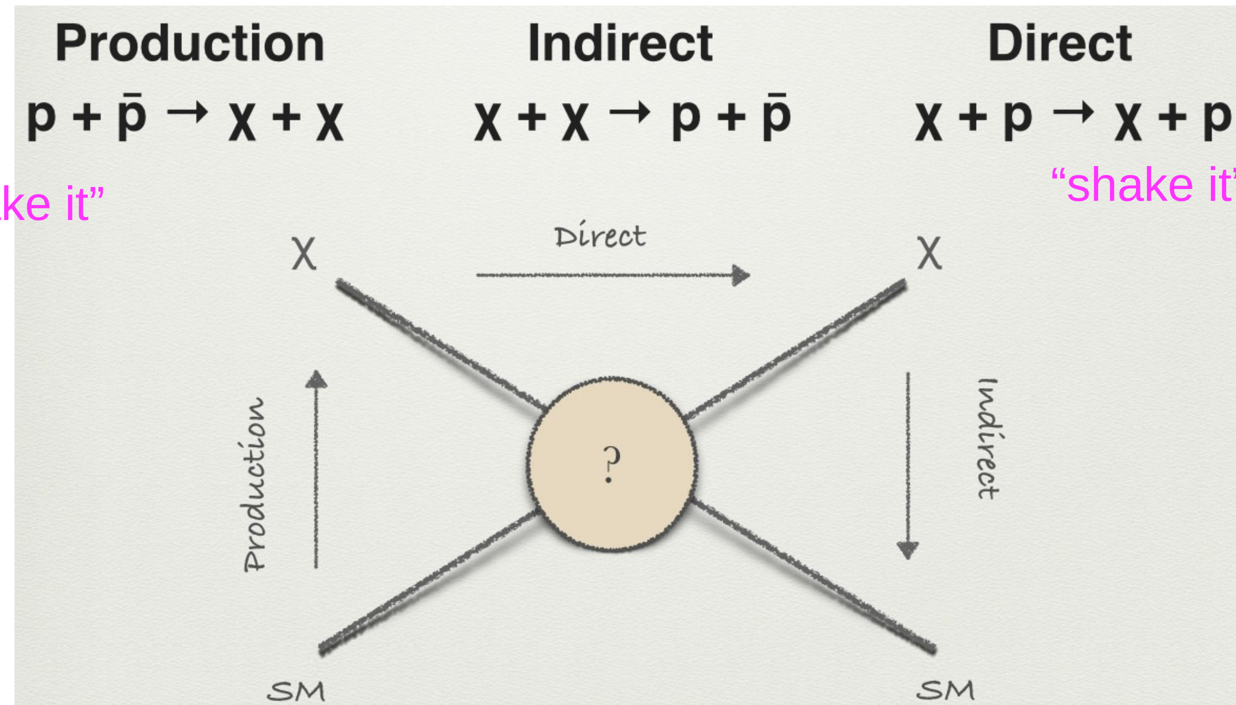
Production	Indirect	Direct
$p + \bar{p} \to \chi + \chi$	$\chi + \chi \to p + \bar{p}$	$\chi + p \to \chi + p$



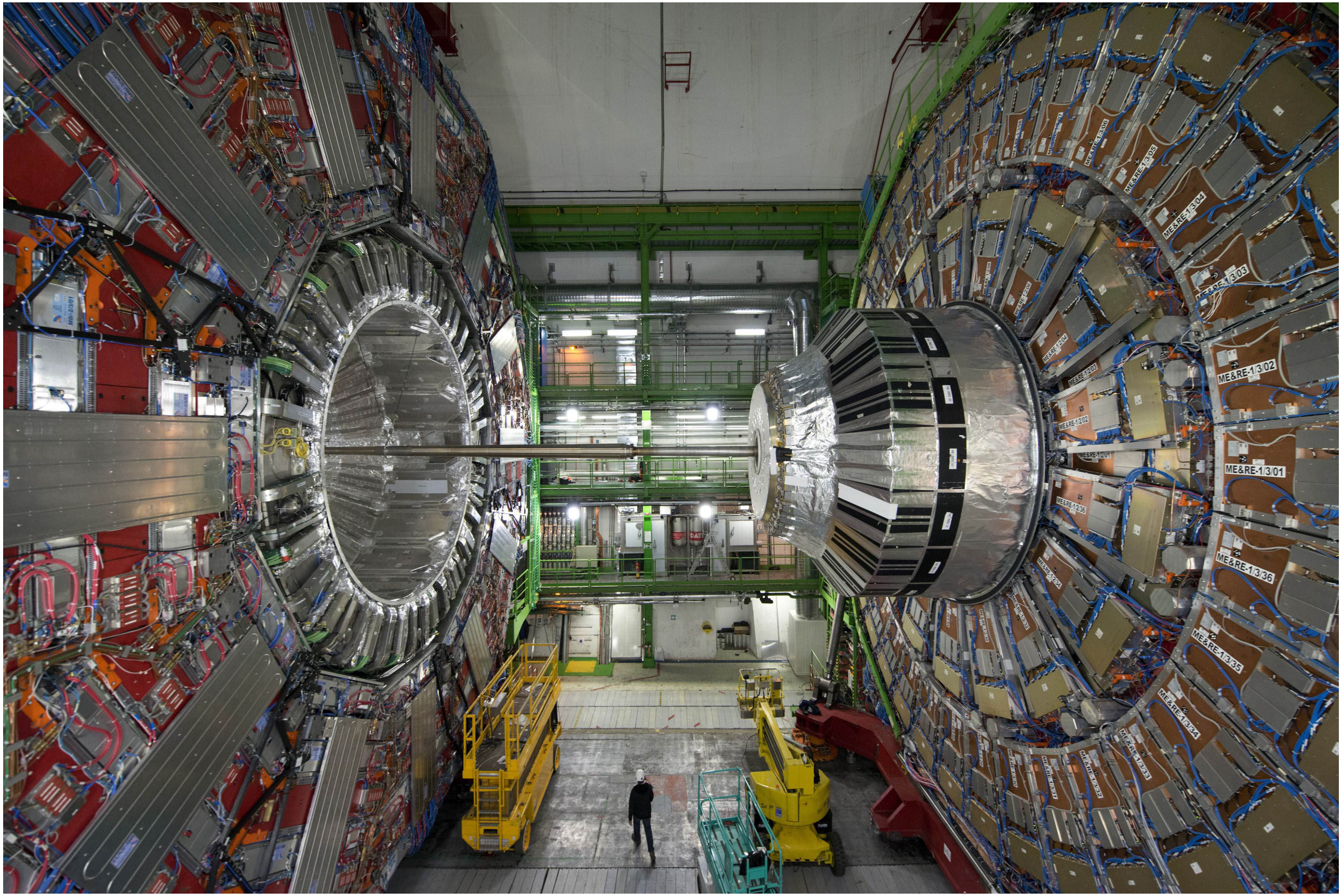
(3) Searches for Dark Matter – production at colliders

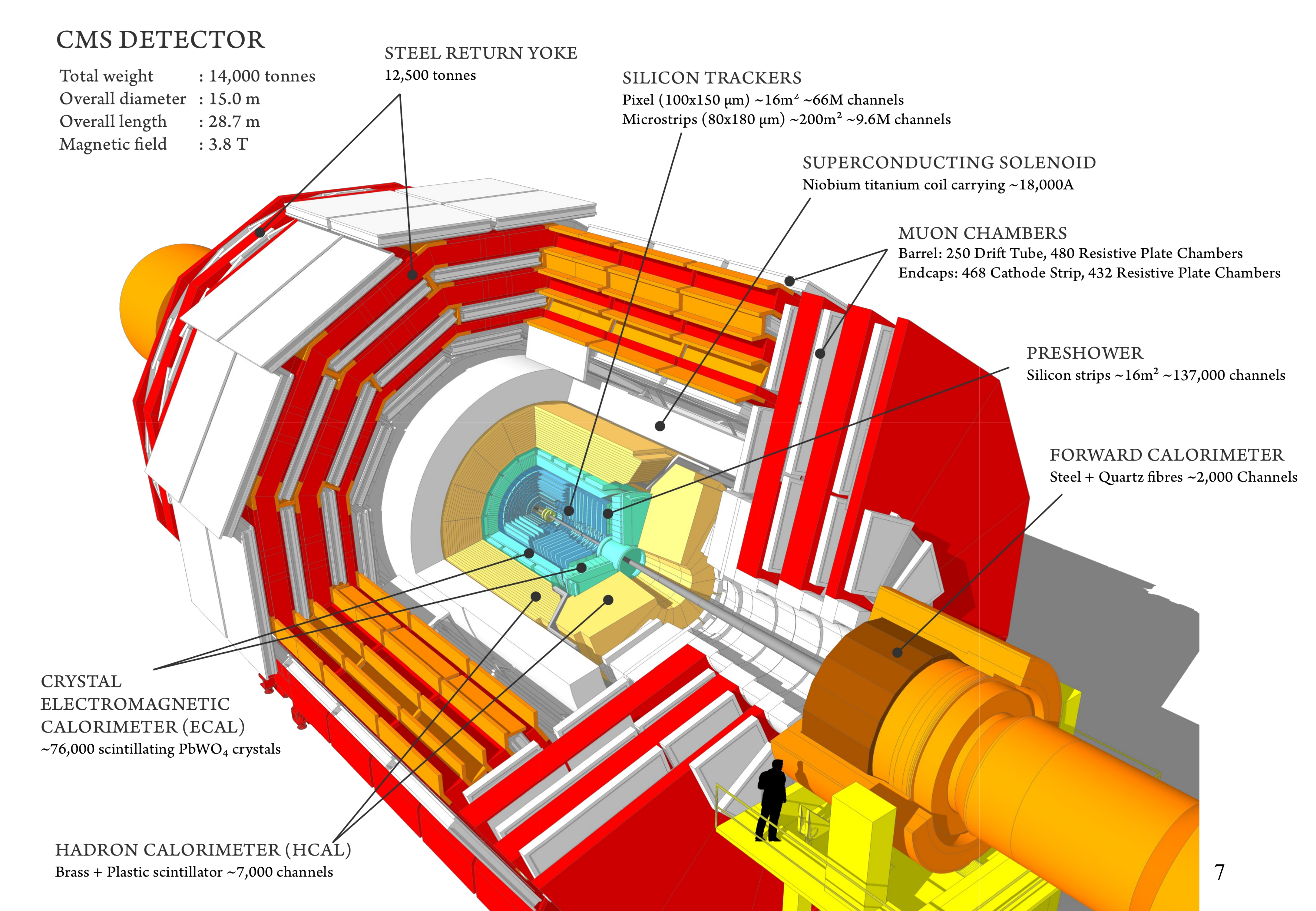
“break it”

“make it”

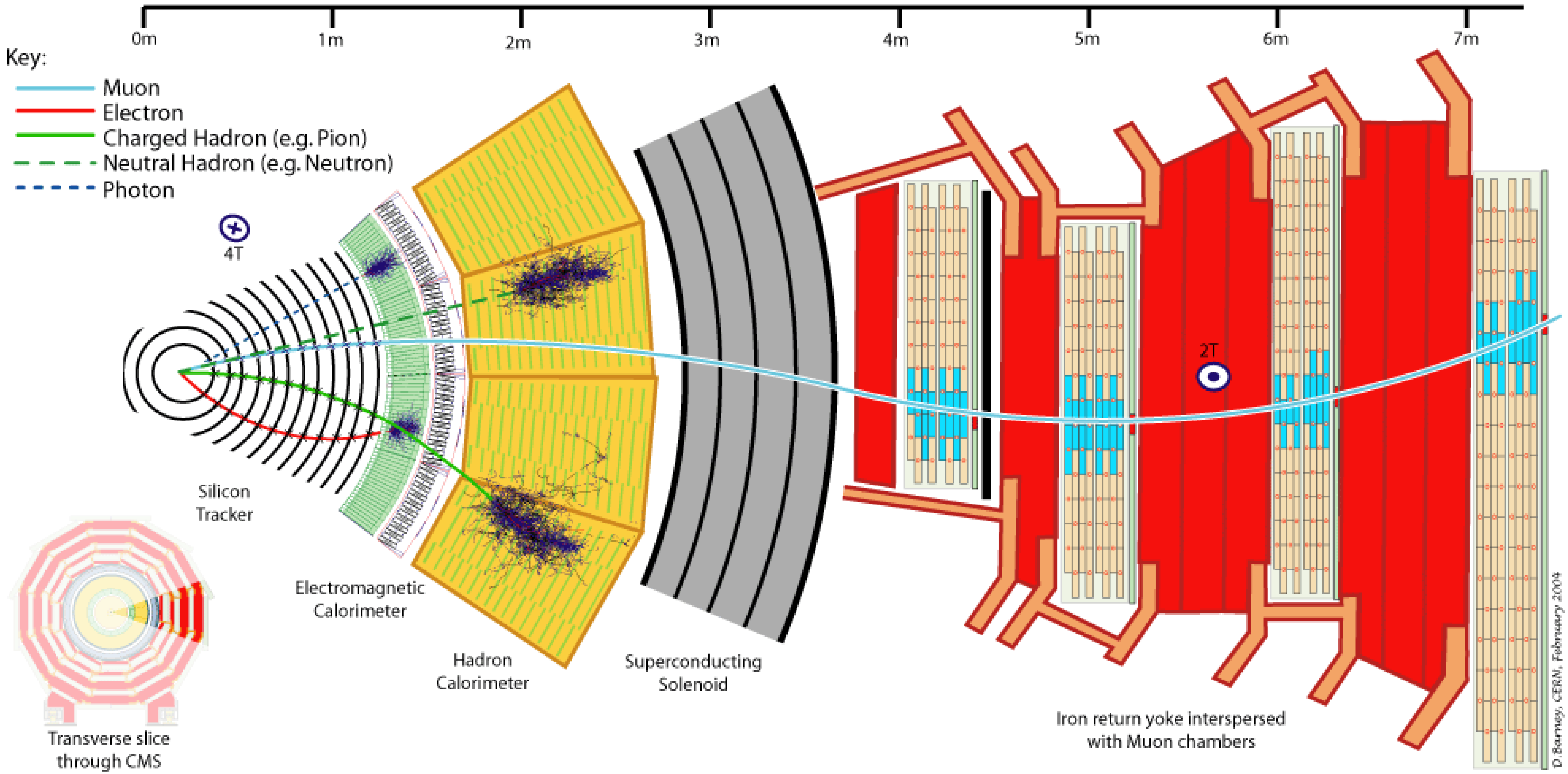


Production at colliders




CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

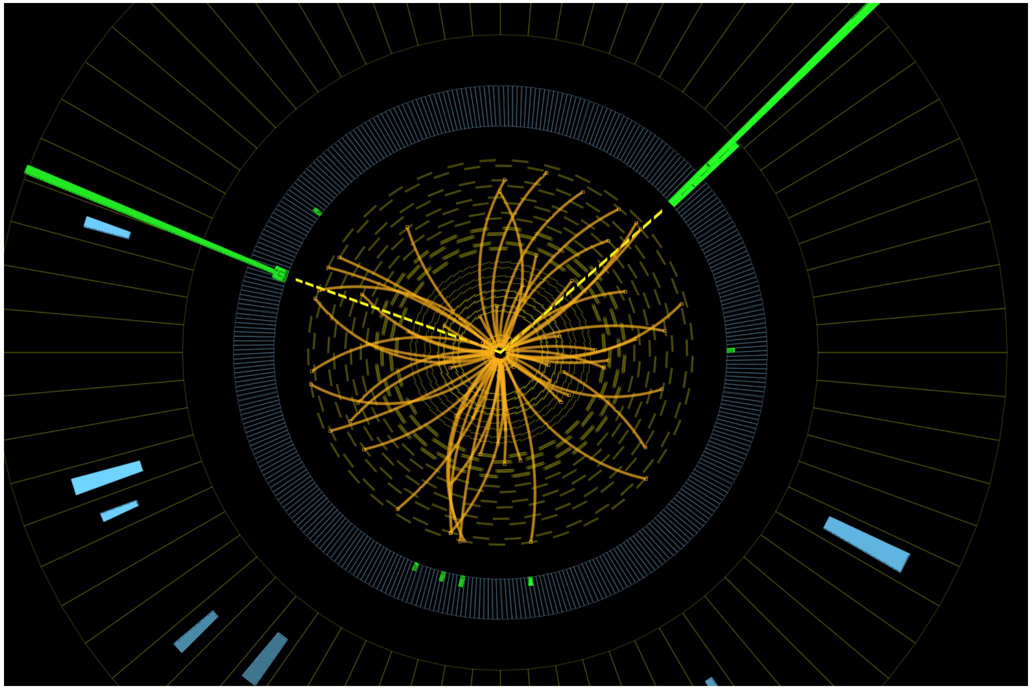
Production at colliders



Production at colliders

– Dark matter does not interact electromagnetically: visible signature at colliders is “missing energy” (apparent violation of conservation of energy)

– Searches for direct production and indirect production via “cascade decays” in e.g. supersymmetric models



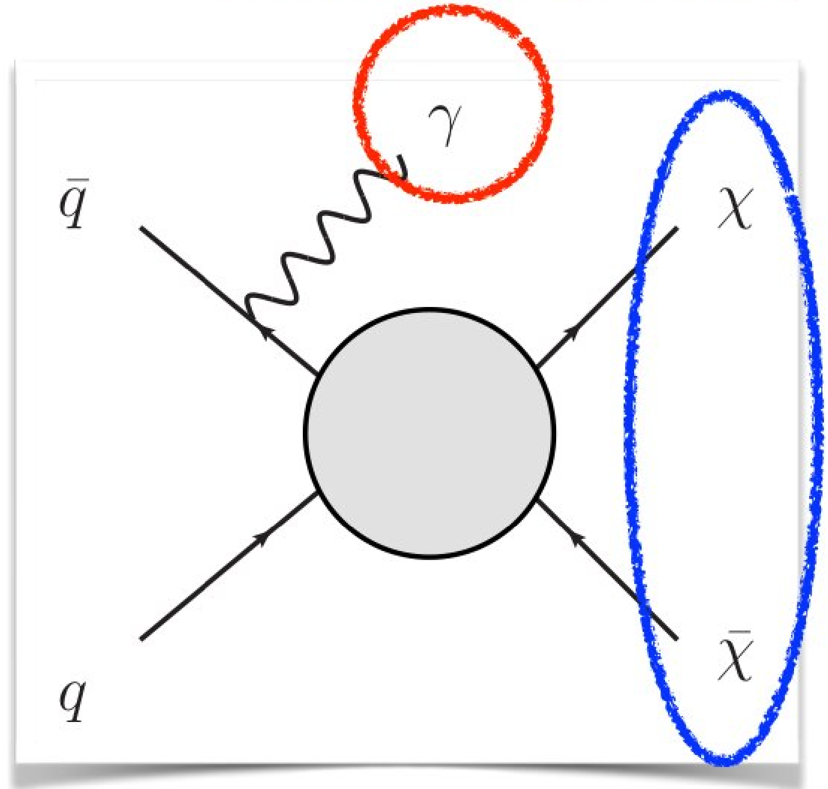
Production at colliders

– Searches for direct production

– Dark matter particles alone wouldnt be detectable

– Need particles radiated off from the "initial" gluons and/or quarks to detect dark matter

trigger and momentum offset in transverse plane



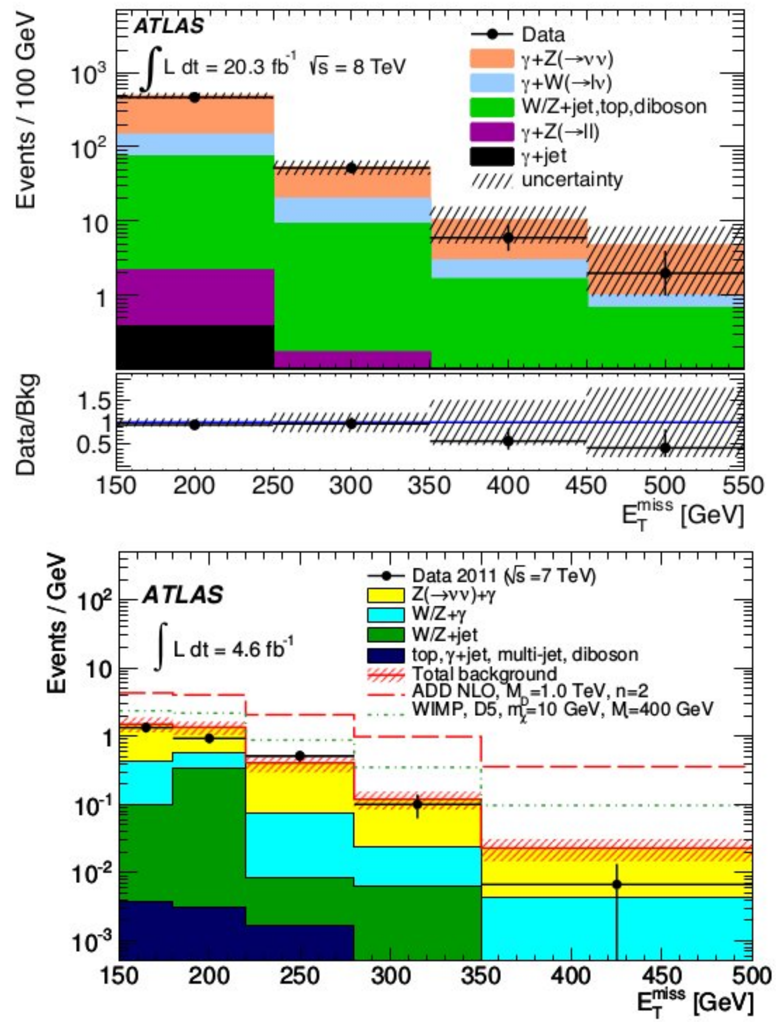
missing energy

Production at colliders

arXiv 1411.1559

– Searches for direct production

Data (black lines and dots) are compared with expected Standard Model backgrounds



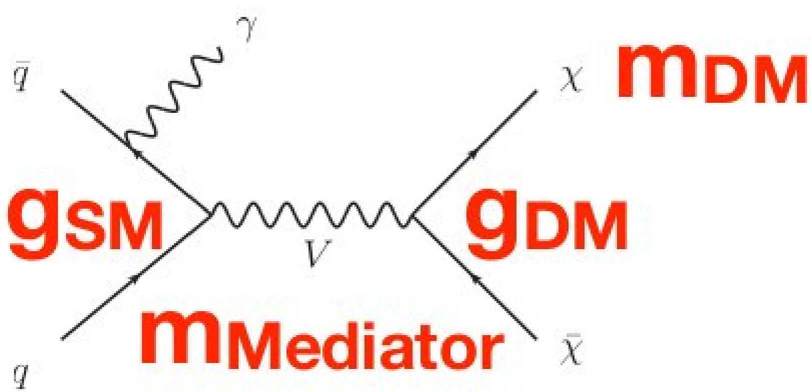
events with high energetic γ selected

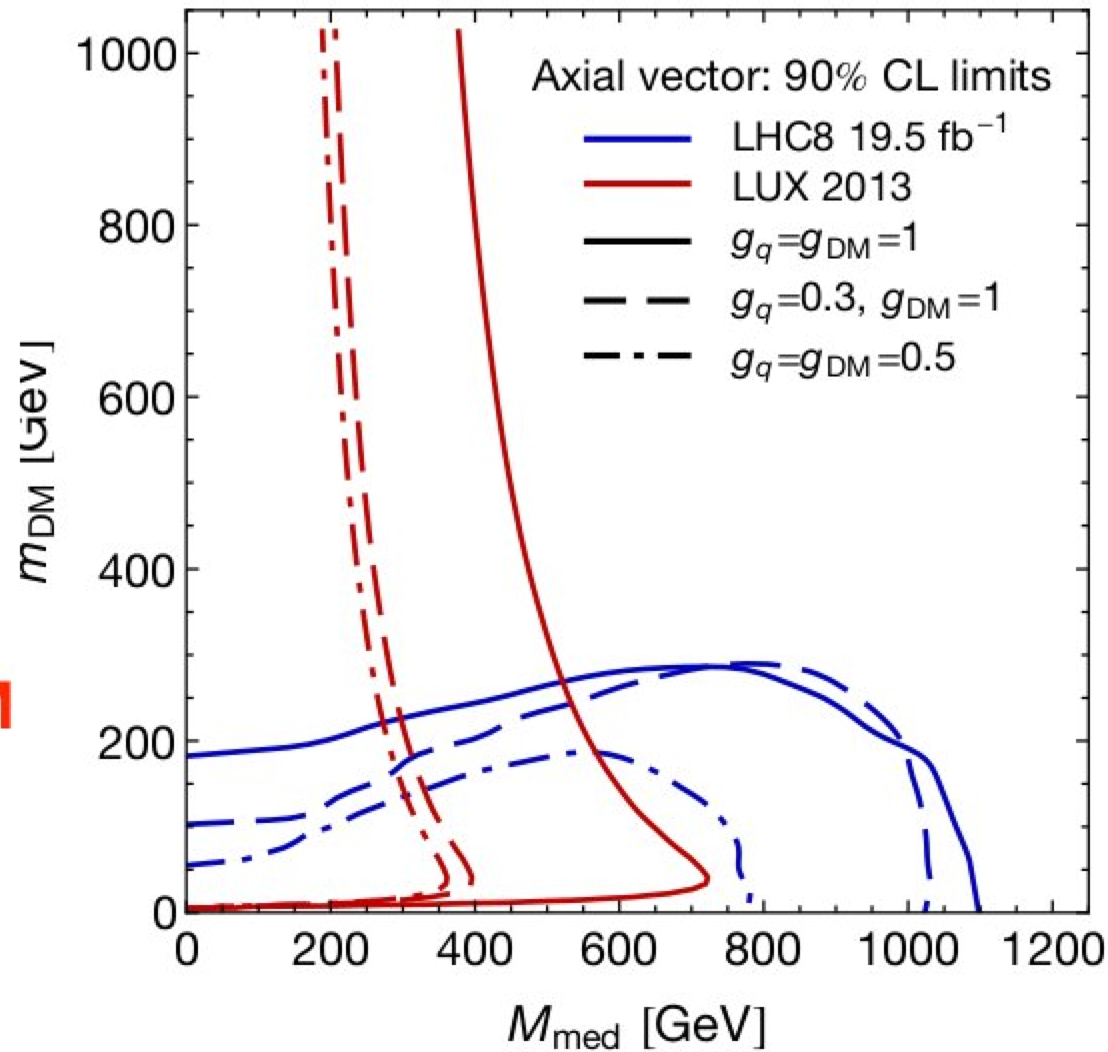
27

Production at colliders

– Searches for direct production

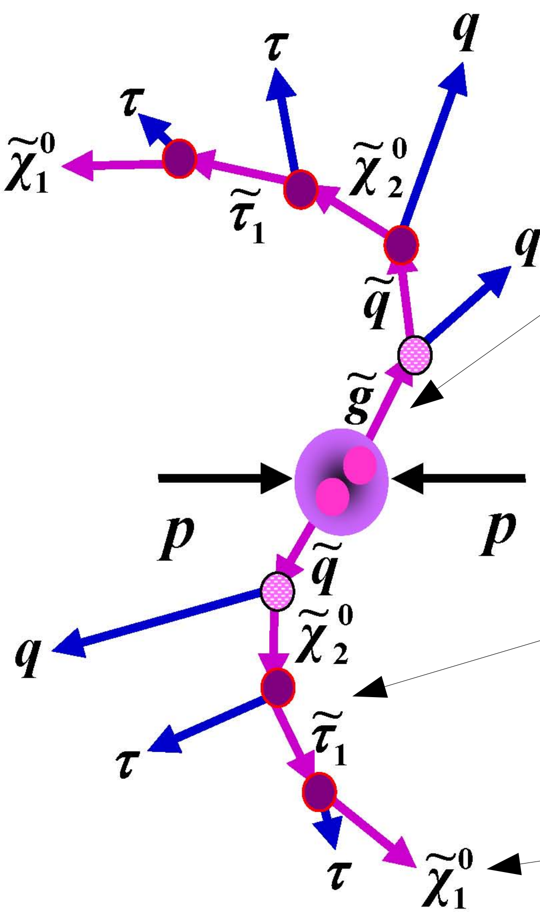
“Negative” results are interpreted as limits on masses of dark matter particle and “mediator” particle.





Production at colliders

– searches for indirect production via cascade decays, in e.g. supersymmetry

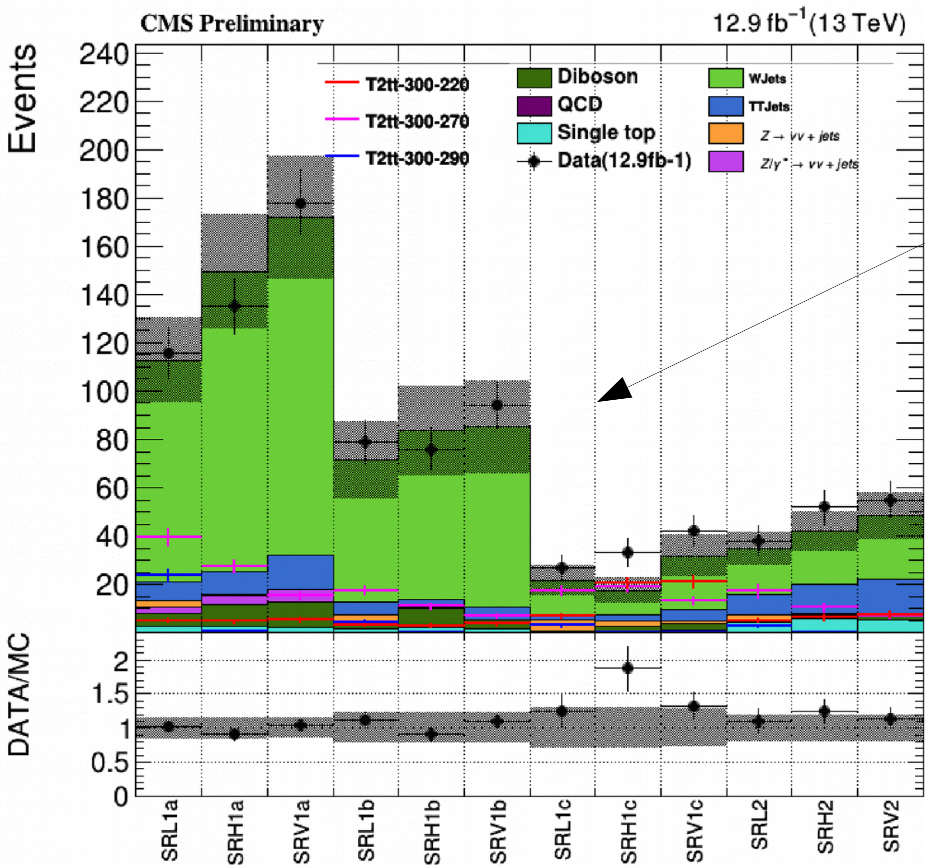


typically “colored” SUSY particles are produced

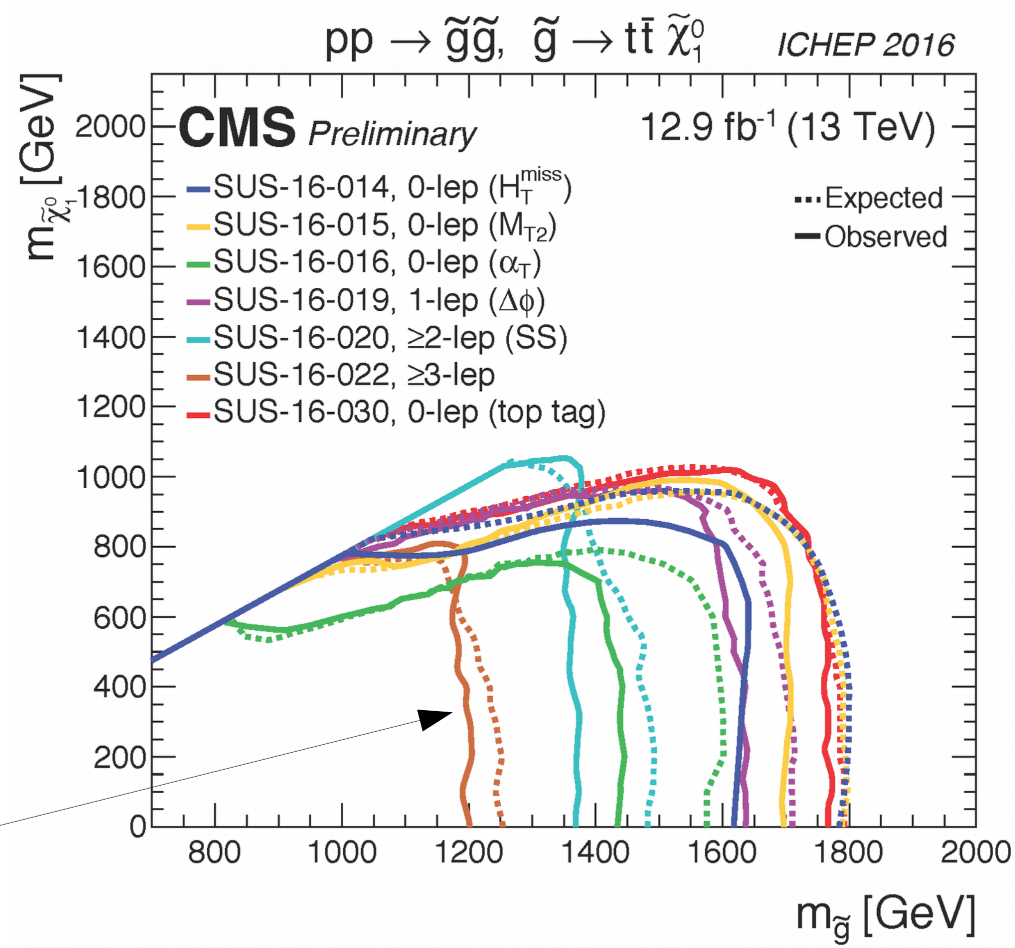
“cascade” decays result in missing energy and “lots of other stuff” as the experimental signature

ends with lightest supersymmetric particle (R parity conservation)

Production at colliders



Result



Interpretation as exclusion

Intermediate summary: production of dark matter at colliders

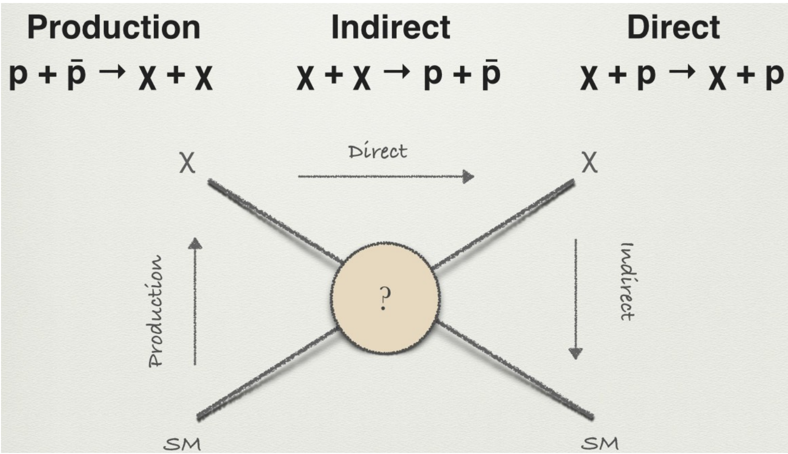
– If WIMPs exist, one should be able to produce them at the LHC

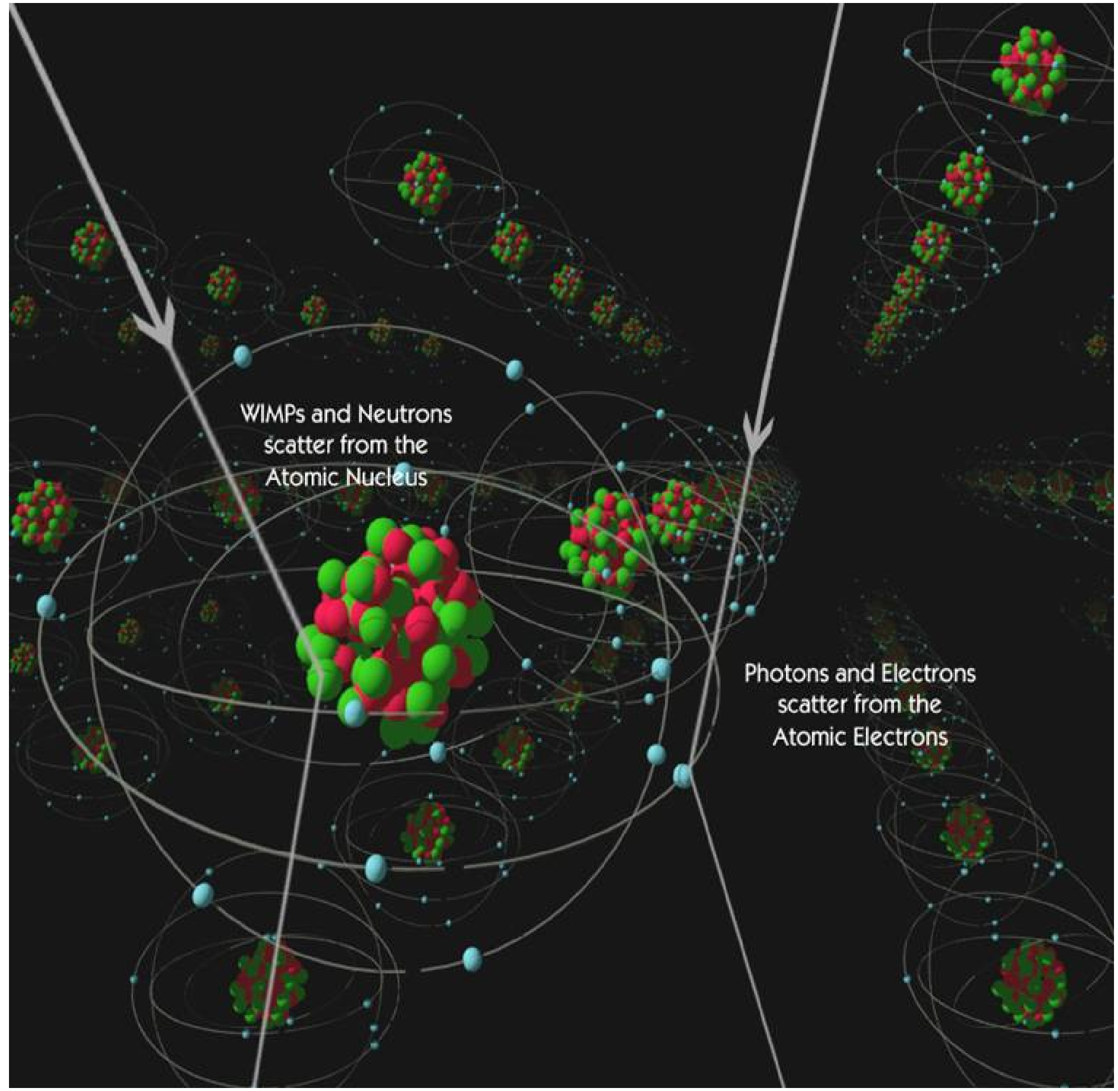
– Direct production of dark matter particles is looked at

– Indirect production of dark matter particles via cascade decays from e.g. colored supersymmetrical particles is also searched for

– No hints have been found so far

Direct detection





WIMP-nucleus interaction

- The interaction of a generic WIMP with nuclei has several contributions

$$\boxed{\sigma_{\chi-N}}$$

Axial-Vector

$$\mathcal{L}_A \sim \bar{\chi}\gamma^{\mu}\gamma_5\chi\,\bar{q}\gamma^{\mu}\gamma_5 q$$

$$\frac{(J+1)}{J}$$

- Adds incoherently

SPIN-DEPENDENT

(Nucl. Angular mom)

Scalar

$$\mathcal{L}_S \sim \bar{\chi}\chi\,\bar{q}q$$

$$A^2$$

SPIN-INDEPENDENT

(Nucleon #)

Vector

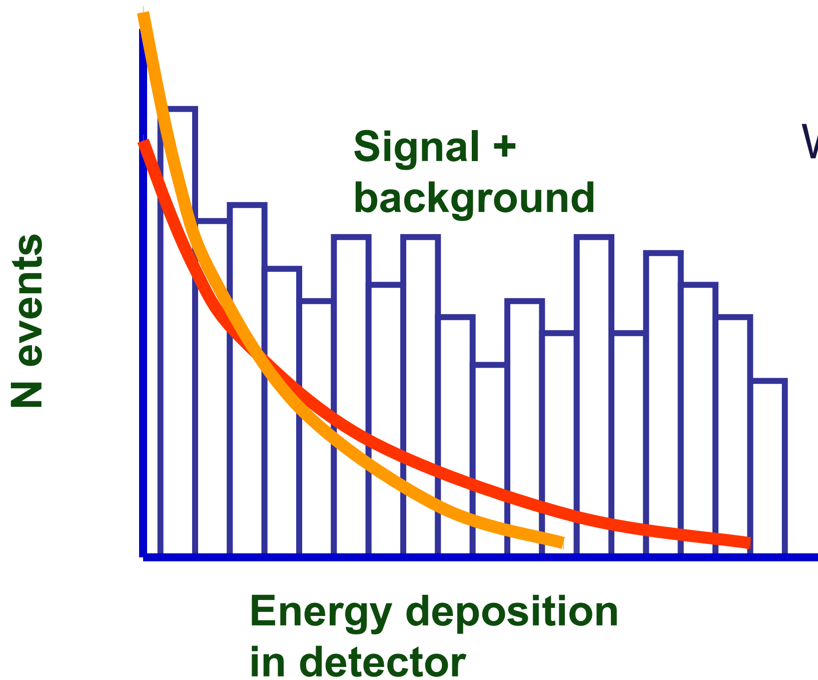
$$\mathcal{L}_V \sim \bar{\chi}\gamma^{\mu}\chi\,\bar{q}\gamma^{\mu}q$$

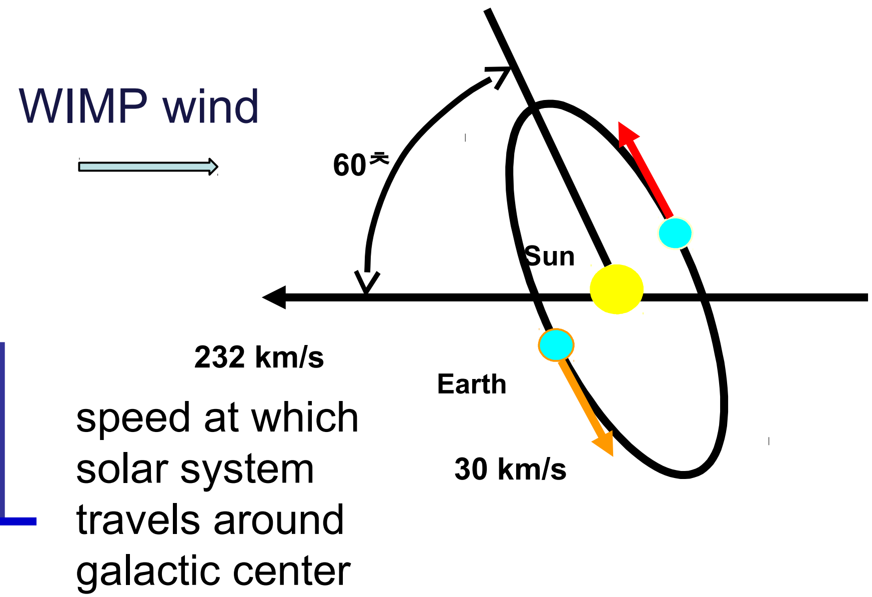
$$A^2$$

- Adds coherently
- Only for non-Majorana WIMPs

SPIN-INDEPENDENT

WIMP detection: annual modulation



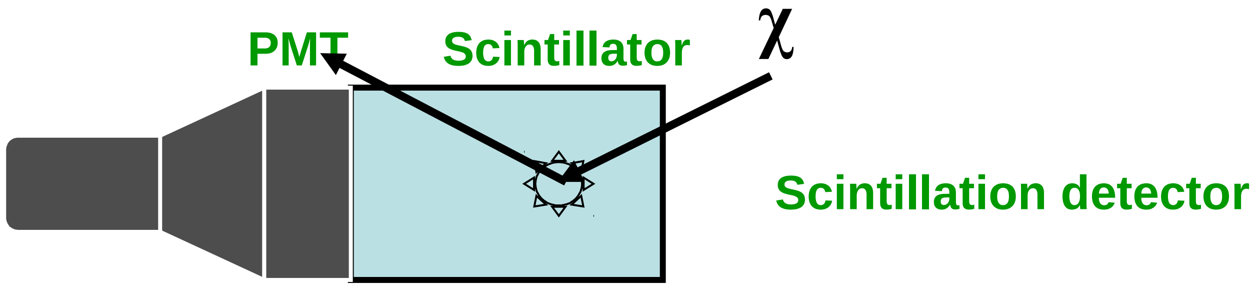


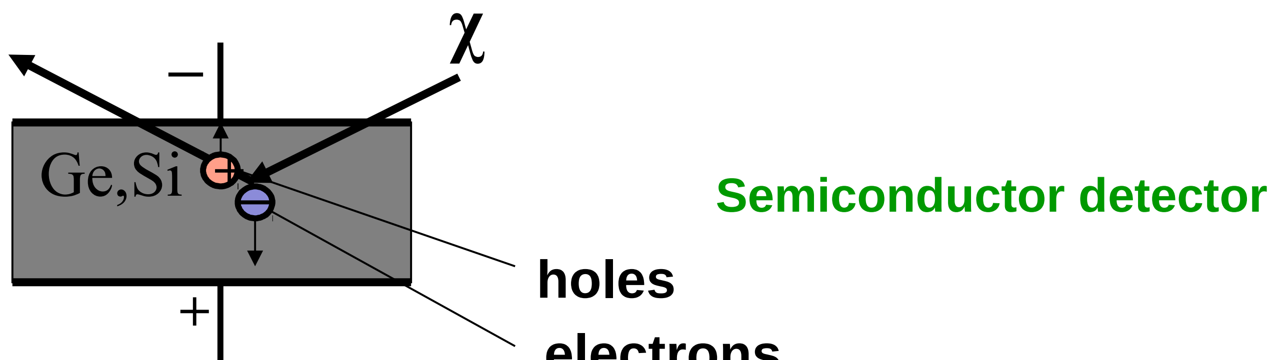
Expected variation of WIMP count rate ~ 5%

WIMP detection: techniques

First generation experiments: detectors from particle physics

used at the beginning in pioneer WIMP experiments:
COSME, IGEX, Heidelberg-Moscow, MIBETA (double beta decay experiments)



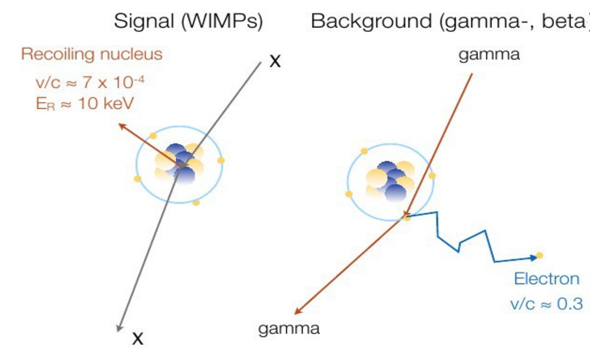


The main disadvantage – single channel of energy deposition

WIMP detection: how to detect?

Second generation: specialised detection techniques

The main goal: to "switch off" background electromagnetic and strong interactions!



By measurements of energy deposition in 2 or more channels => rejection of electron recoils

Active neutron veto. For nuclear recoil events, by selection only single scatters in a central target => rejection of neutron scattering off atomic nuclei.

WIMP must scatter only once!

WIMP detection: background reduction

Your typical WIMP detector:

’Onion-like’ shielding structure where each layer targets a specific background

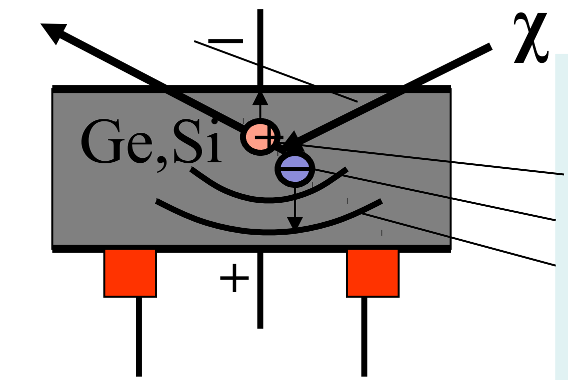
- Water or polyethylene, given their hydrogen content, stop neutrons and, if the water is made active with photomultipliers, also may tag muons and associated particles

- High purity copper and lead, typically placed in the inner layers, stop gamma radiation to enter the detector

- Discrimination techniques, based either on the shape of the pulses or on the use of multiple detection channels (scintillation light, ionisation charge or phonons) further enhance the signal to noise ratio, allowing to single out samples of nuclear recoil events with high efficiency.

WIMP detection: techniques

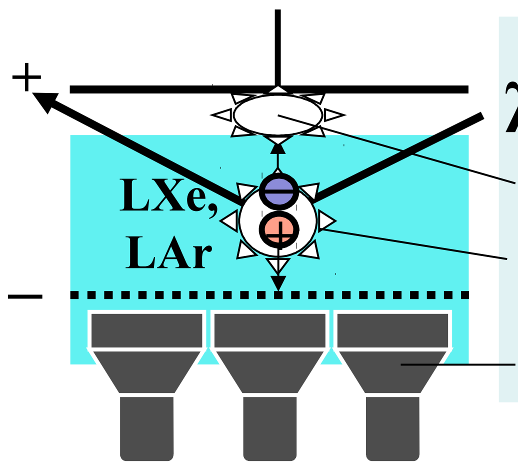
Two-channel measurement of energy deposition



holes
electrons
phonons
thermistors

Low-temperature bolometers

Particles produce ionisation and heat
heating up the crystal by ~10^{-6} K
Operate at T ~ tens mK



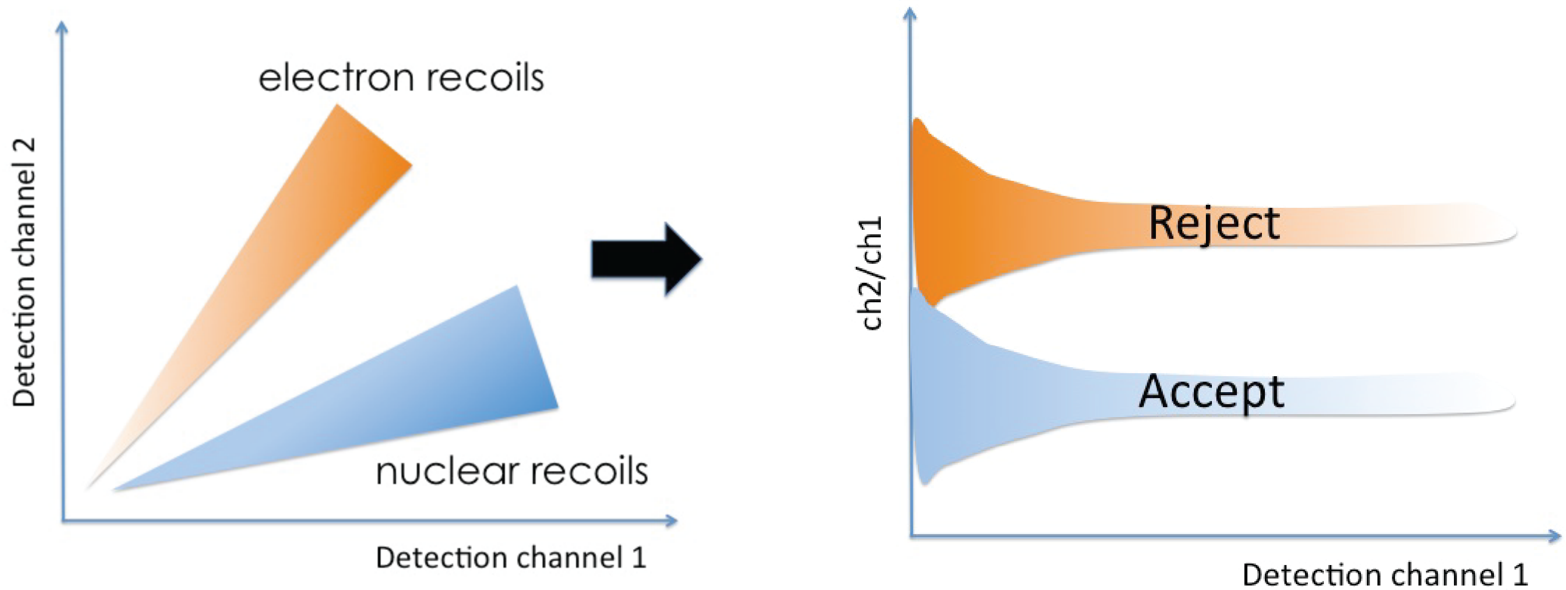
electroluminescence EL
scintillation SC
PMTs

Two-phase noble gas detectors

Particles produce
scintillation and ionisation
Operate at T ~ 100 K

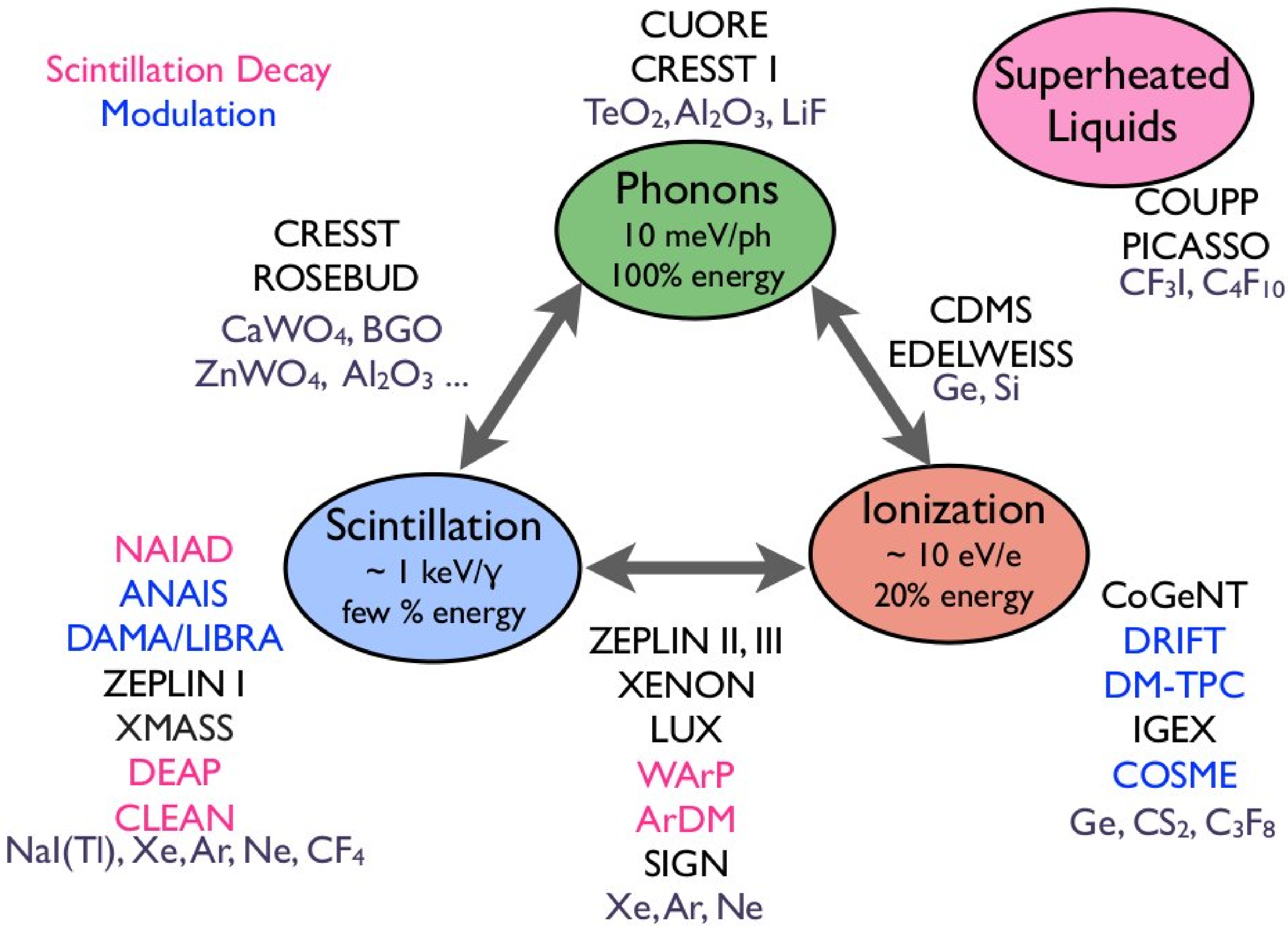
WIMP detection: techniques

Two-channel measurement of energy deposition



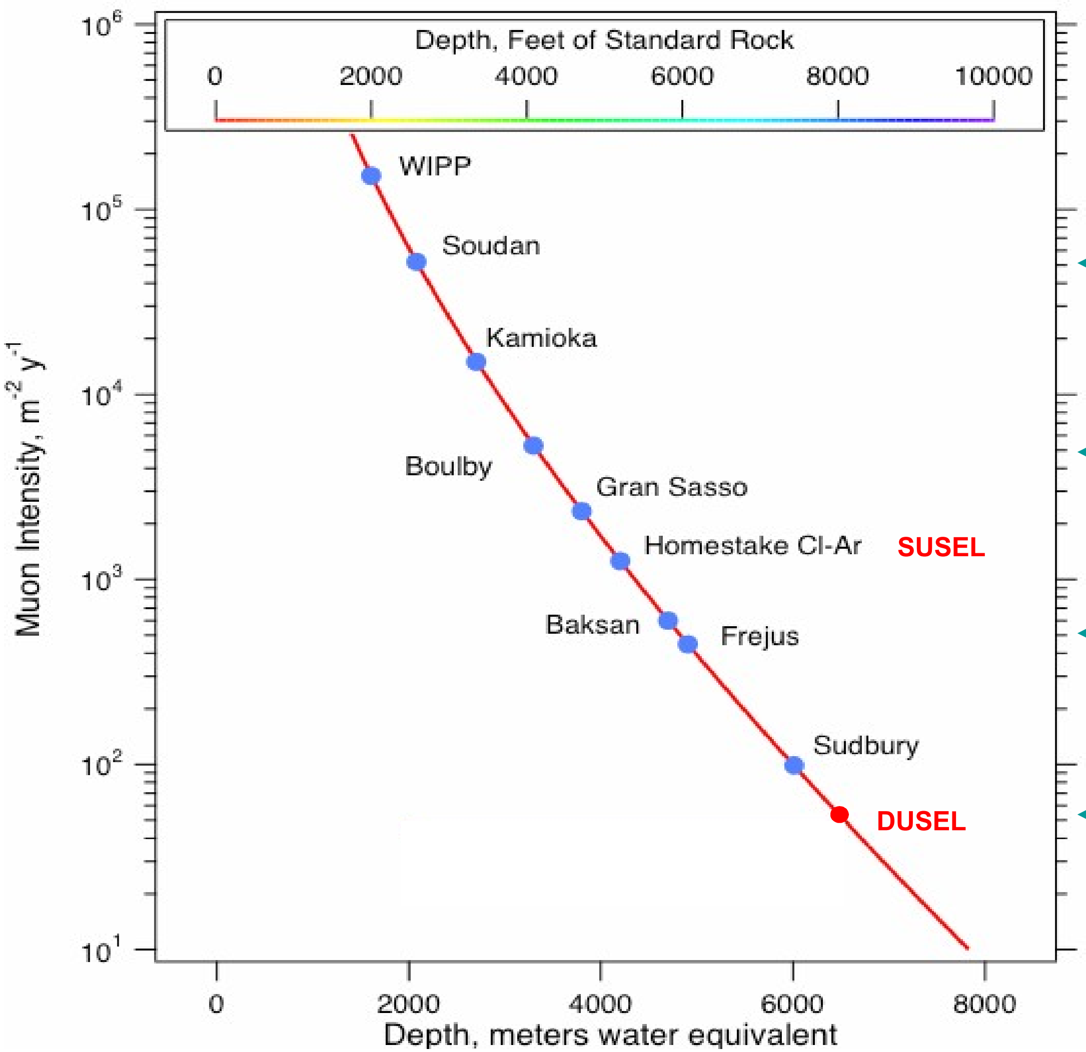
Many DM direct search experiments use two detection channels out of the three available (scintillation light, ionisation charge, phonons). Because the yield of nuclear recoils in one of the channels is usually different from electron recoils, two separated event populations are identifiable in the Ch1 vs Ch2 phase space (left). A rejection criterion can then be defined (right) based on pre-defined acceptance regions.

Measurement of Recoil Energy deposited by WIMPs



WIMP detection: background reduction

The experiments are carried out in underground labs



reduction of muon flux by:

10^5

10^6

10^7

10^8

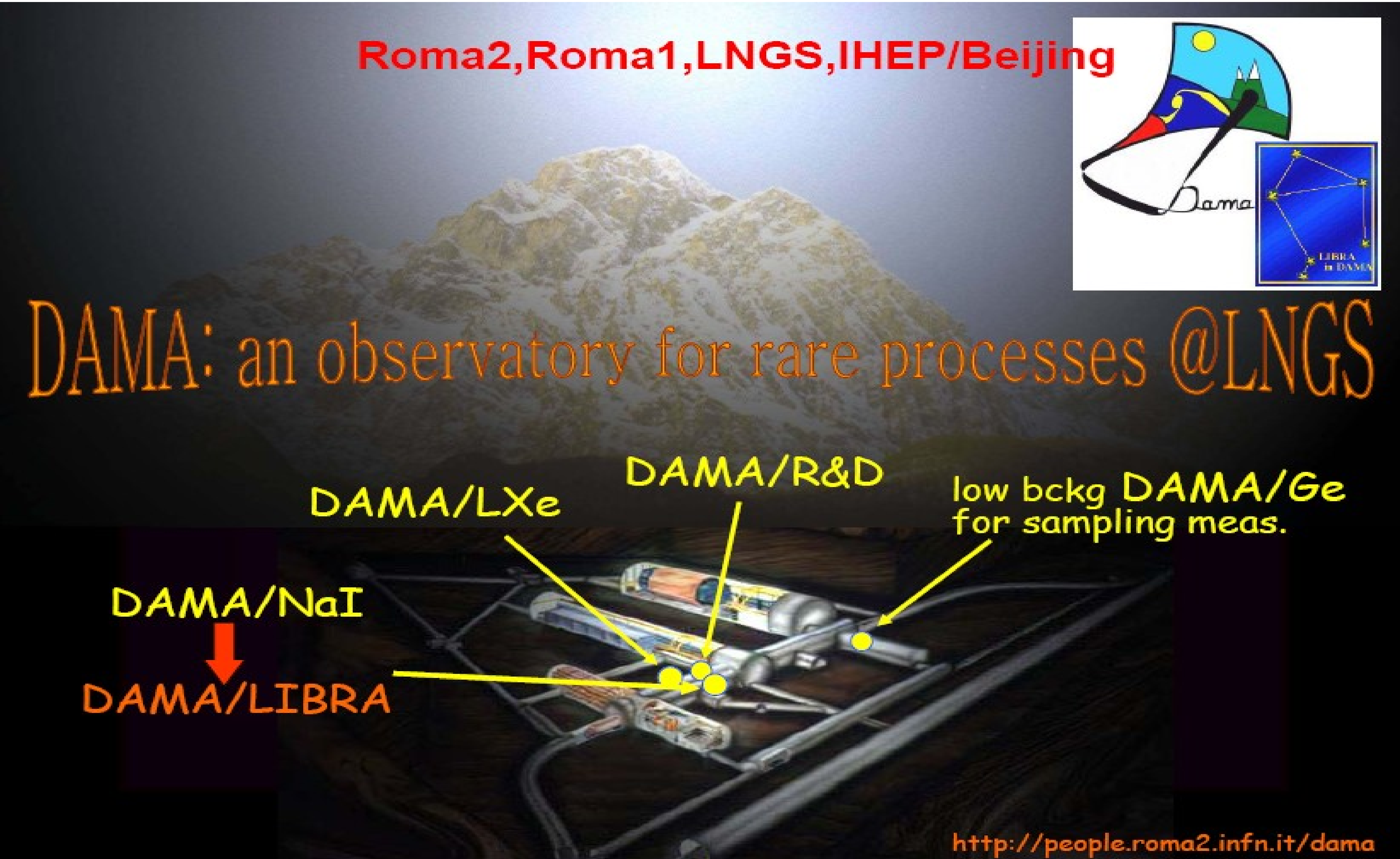
Muon flux at sea level:

$\sim 1\ cm^{-2}\ min^{-1}$

$=$

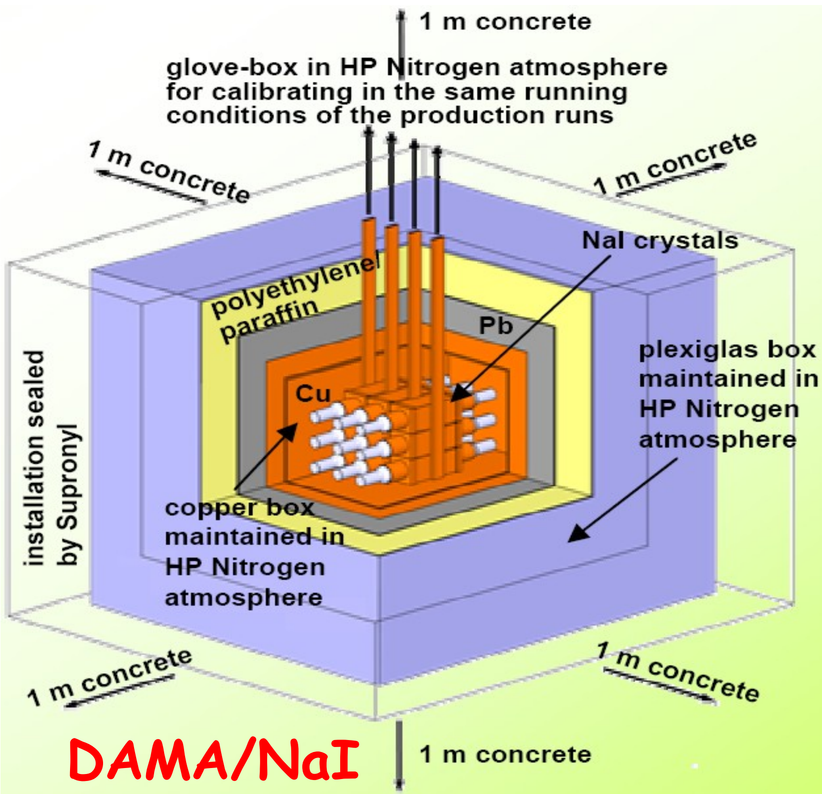
$\sim 5 \cdot 10^9\ m^{-2}\ y^{-1}$

Experiments: DAMA / LIBRA



Experiments: DAMA / LIBRA

9 crystals NaI(Tl) 9,7 kg each, placed in a copper box, then lead, polyethylene, paraffin and enclosed in a plexiglas box filled with high-purity nitrogen to protect from radon (Rn)



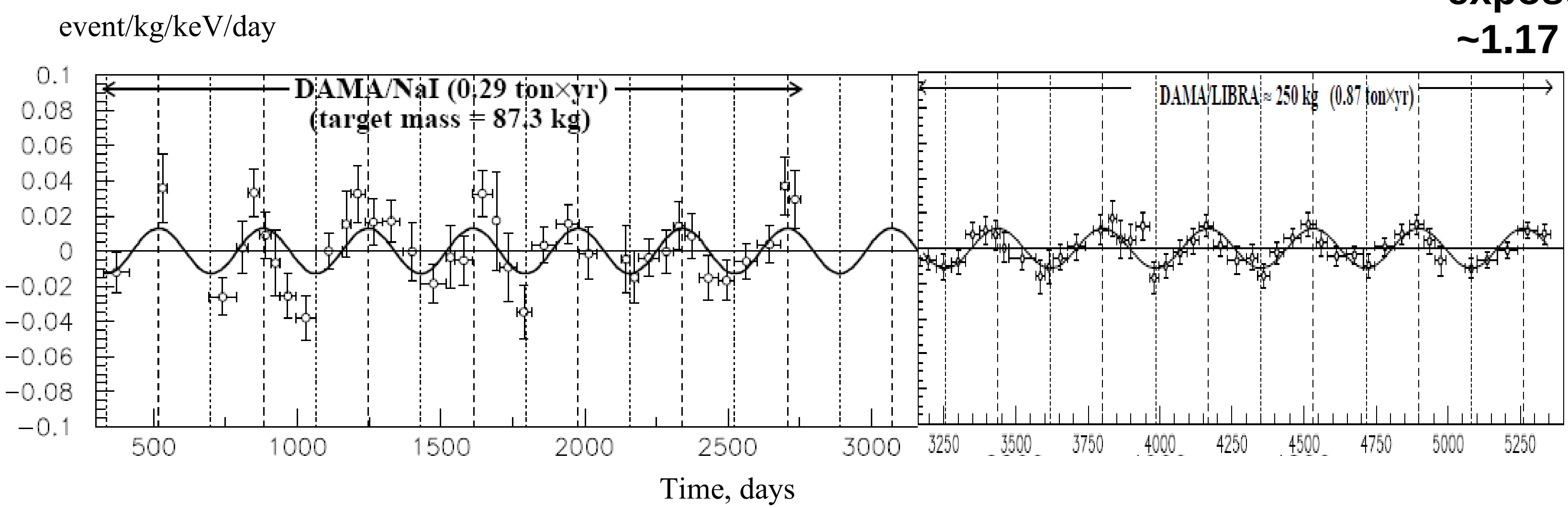
LIBRA- 25 of the same type in the same shield; 250 kg.
Data taking with LIBRA 2003 - 2008

Experiments: DAMA / LIBRA

Deviation of the count rate from the mean value (2 – 6 keV only) during the whole exposure time on both setups DAMA and LIBRA

arXiv:1002.1028 [astro-ph.GA]

Total exposure ~1.17 t·y



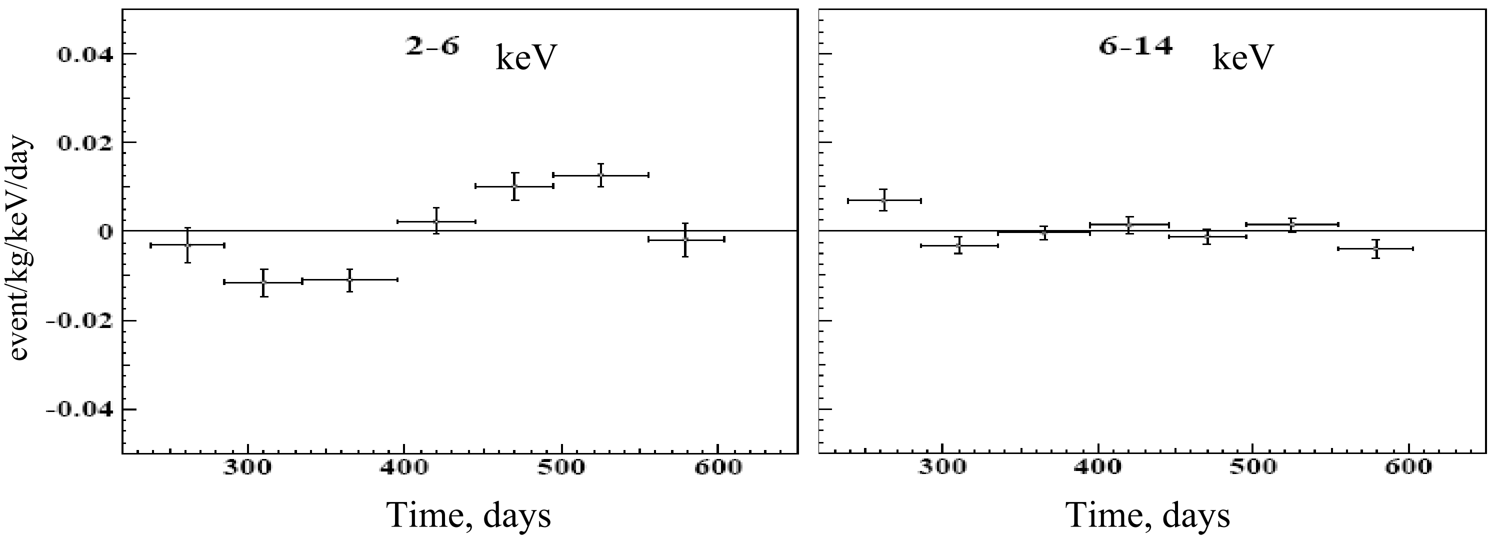
$A \cdot \cos \omega(t - t_0)$ with a period $T = 2\pi/\omega = 0.999 \pm 0.002$ y,

and a phase $t_0 = 146 \pm 7$ day, which is very close to the expected: 152,5 days (2 June)

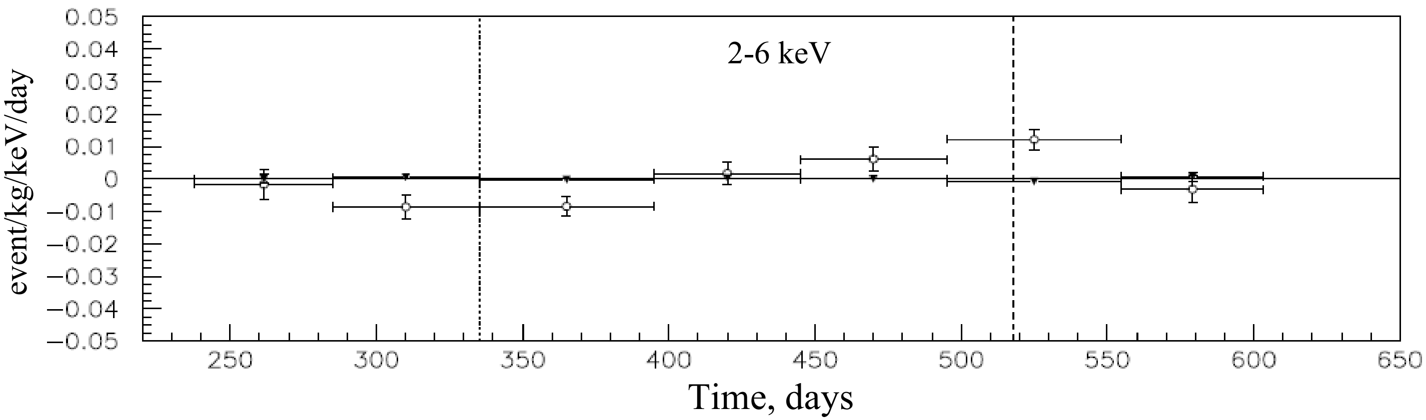
A=(0.0114±0.0013) event/kg/keV/day, Confidence Level = 8.8σ

Experiments: DAMA / LIBRA

Data reduced to one period:



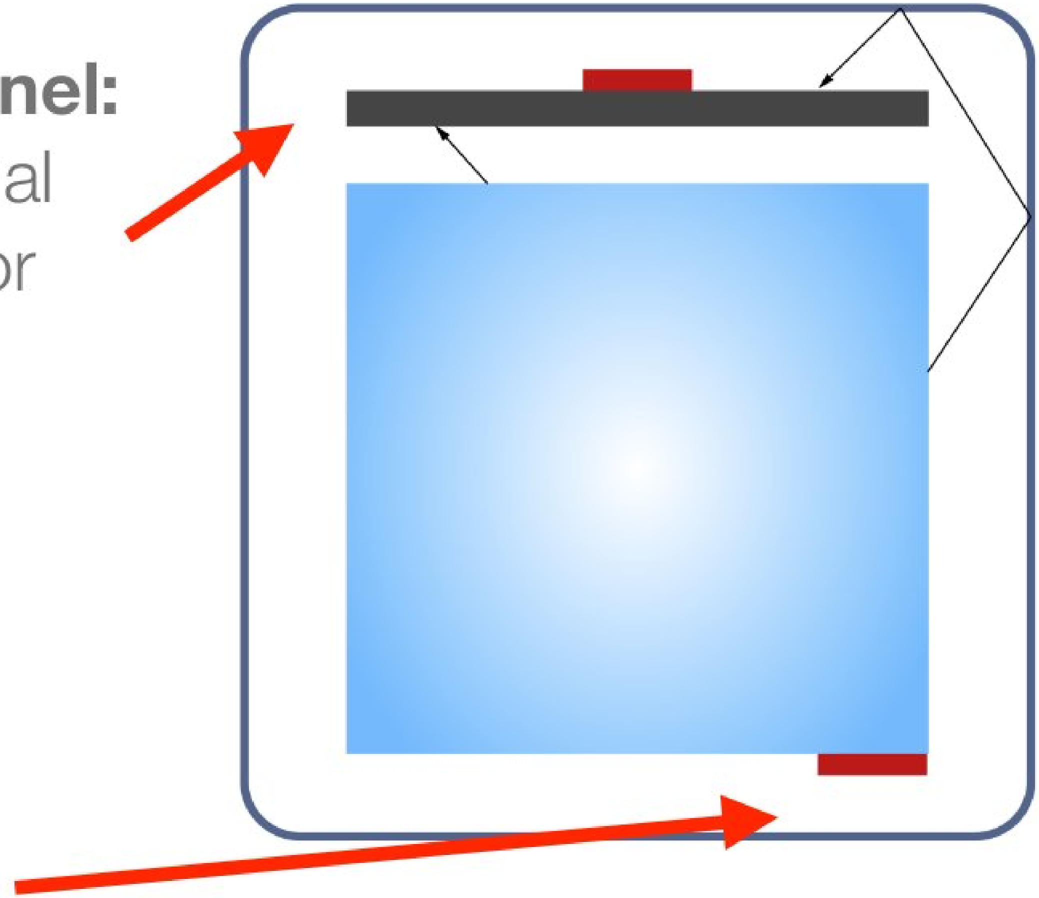
The effect takes place **only in 2-6- keV interval**



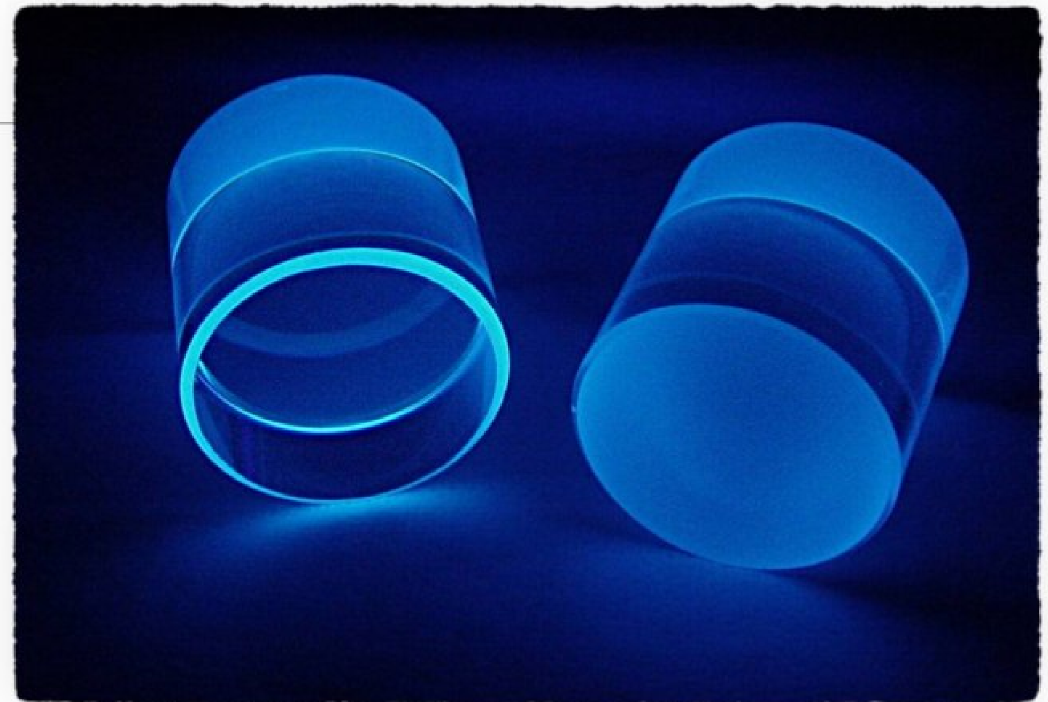
The effect takes place **only for single "hits"!**

Direct Dark Matter Detection with cryogenic Detectors

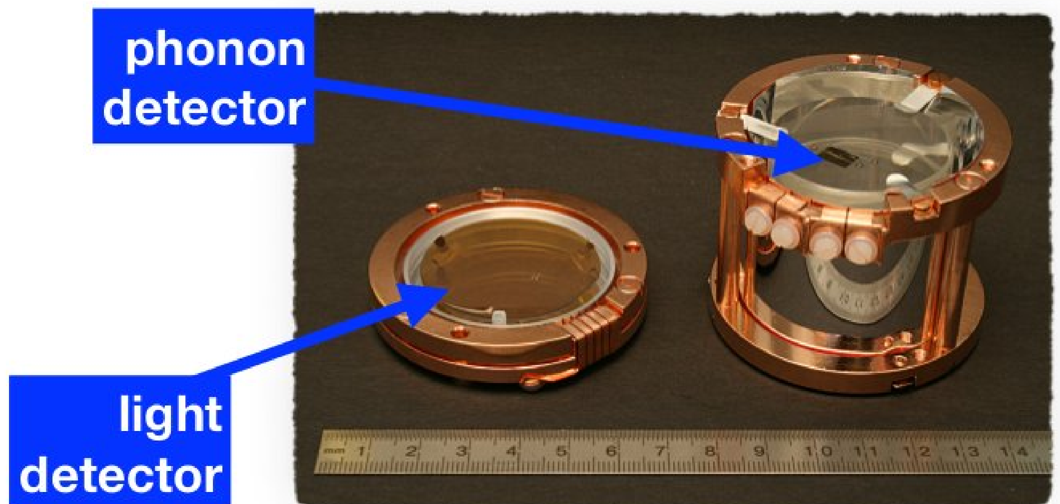
- CRESST: two read out channels
  - **(scintillation) light channel:** different response for signal and background events for background rejection ("quenching")
  - **phonon channel:** measurement of total deposited energy (=recoil energy)



Direct Dark Matter Detection with cryogenic Detectors

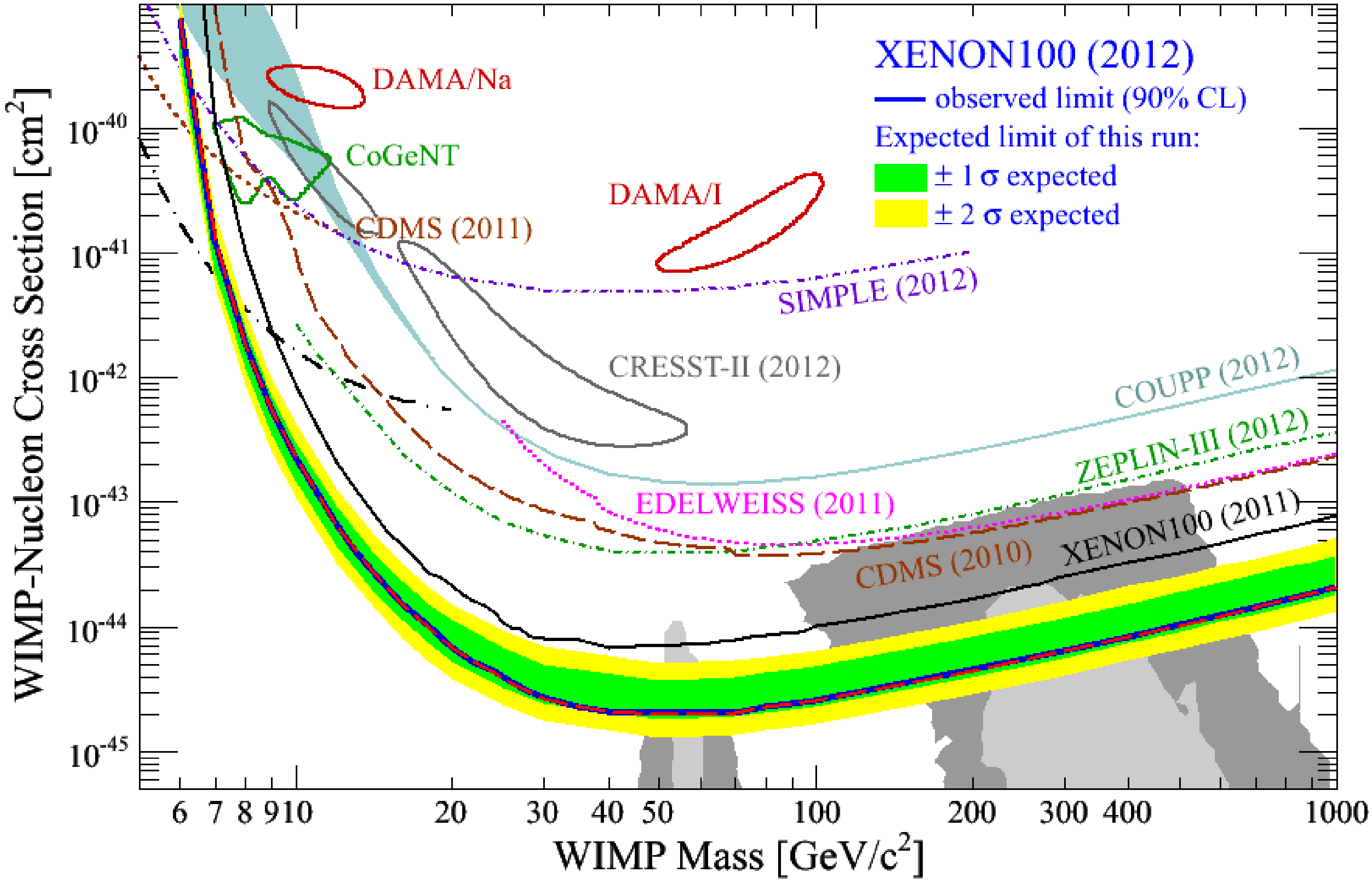


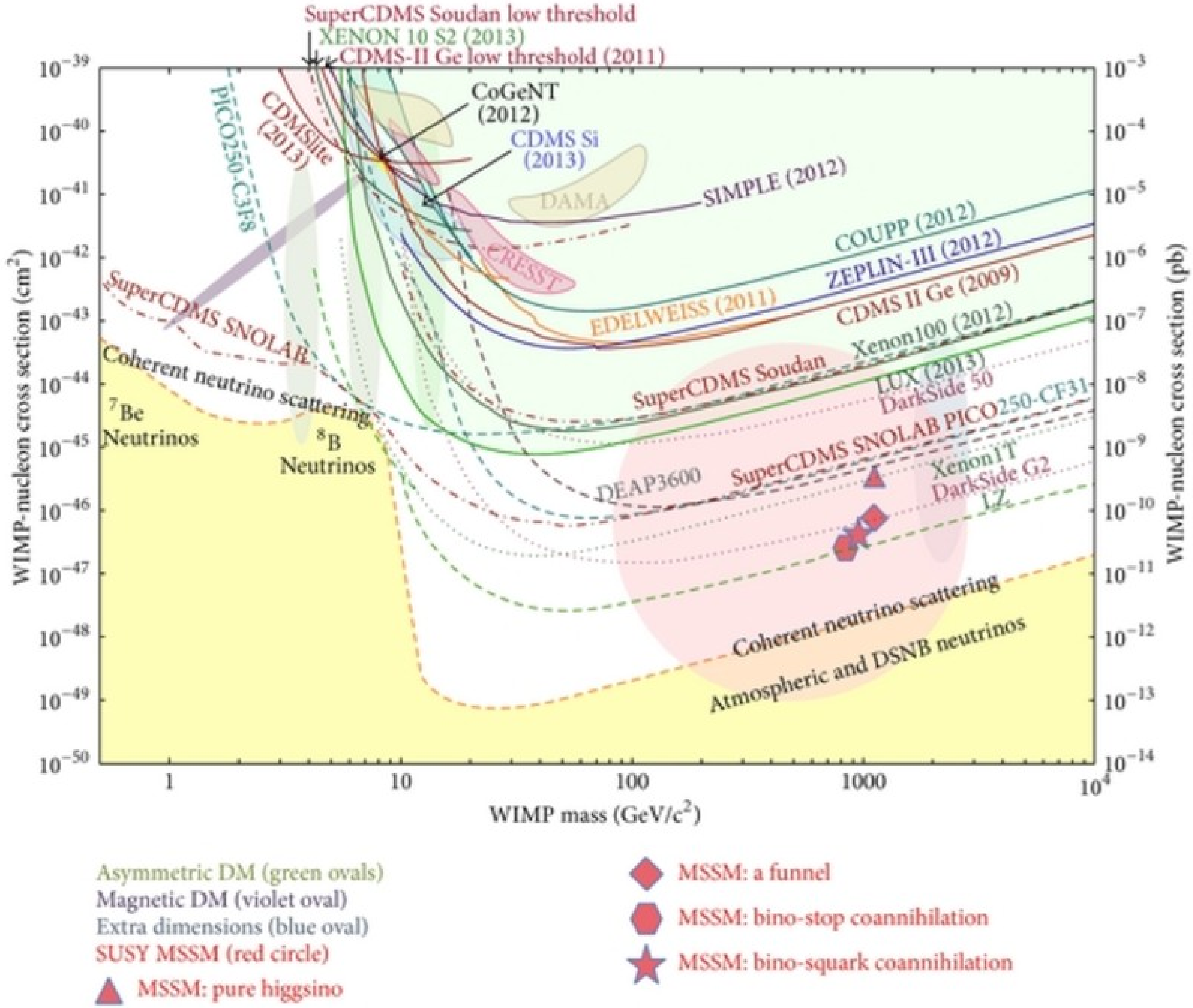
- CRESST II uses $CaWO_4$ crystals operated at ~ 15 mK
- ΔE~10 keV recoil energy leads to ΔT~10 µK temperature rise
- detect temperature change with transition edge sensor (TES)



Current results

DAMA, CRESST and COGeNT see positive results in contradiction with each other as well as with other results.




SuperCDMS Soudan low threshold
XENON 10 S2 (2013)
CDMS-II Ge low threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
CDMSlite (2013)
PICO250-C3F8
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011)
CDMS II Ge (2009)
Xenon100 (2012)
SuperCDMS SNOLAB
SuperCDMS Soudan
LUX (2013)
DarkSide 50
Coherent neutrino scattering
PICO250-CF3I
SuperCDMS SNOLAB
^{7}Be Neutrinos
^{8}B Neutrinos
DEAP3600
Xenon1T
DarkSide G2
LZ
Coherent neutrino scattering
Atmospheric and DSNB neutrinos
WIMP-nucleon cross section (cm^2)
WIMP-nucleon cross section (pb)
WIMP mass (GeV/c^2)
Asymmetric DM (green ovals)
Magnetic DM (violet oval)
Extra dimensions (blue oval)
SUSY MSSM (red circle)
MSSM: pure higgsino
MSSM: a funnel
MSSM: bino-stop coannihilation
MSSM: bino-squark coannihilation

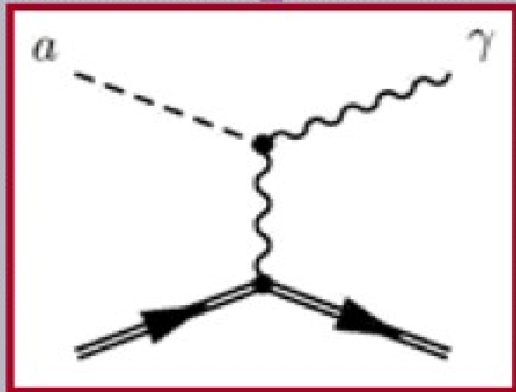
Intermediate Summary direct Dark Matter Detection

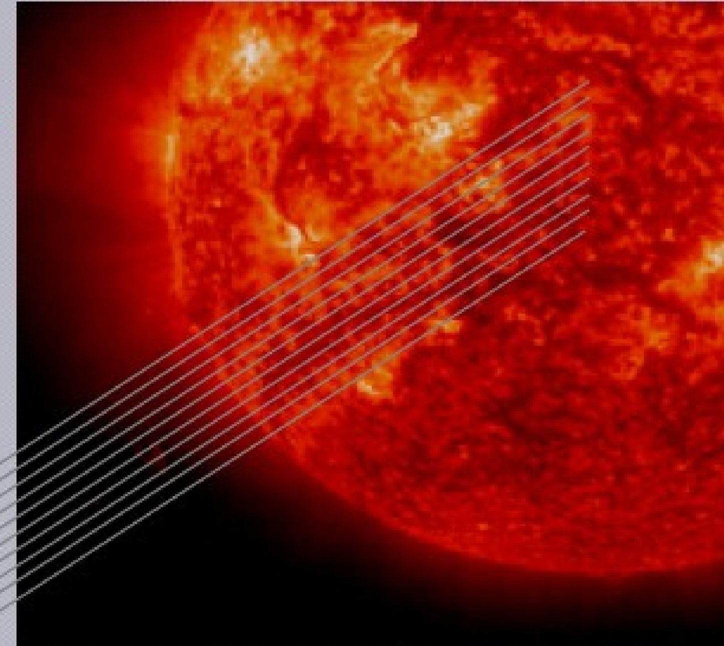
- direct dark matter detection directly probes relic dark matter particles
- dependence on astrophysical models for dark matter distribution (less compared to indirect dark matter searches)
- best sensitivity for O(10-100 GeV) dark matter particles - WIMPS
    - sensitivity to O(1 GeV) dark matter soon similar to LHC experiments
- different mass ranges have different experimental challenges — exposure (high mass) versus threshold (low mass)
- some claims for dark matter detection which are still unexplained

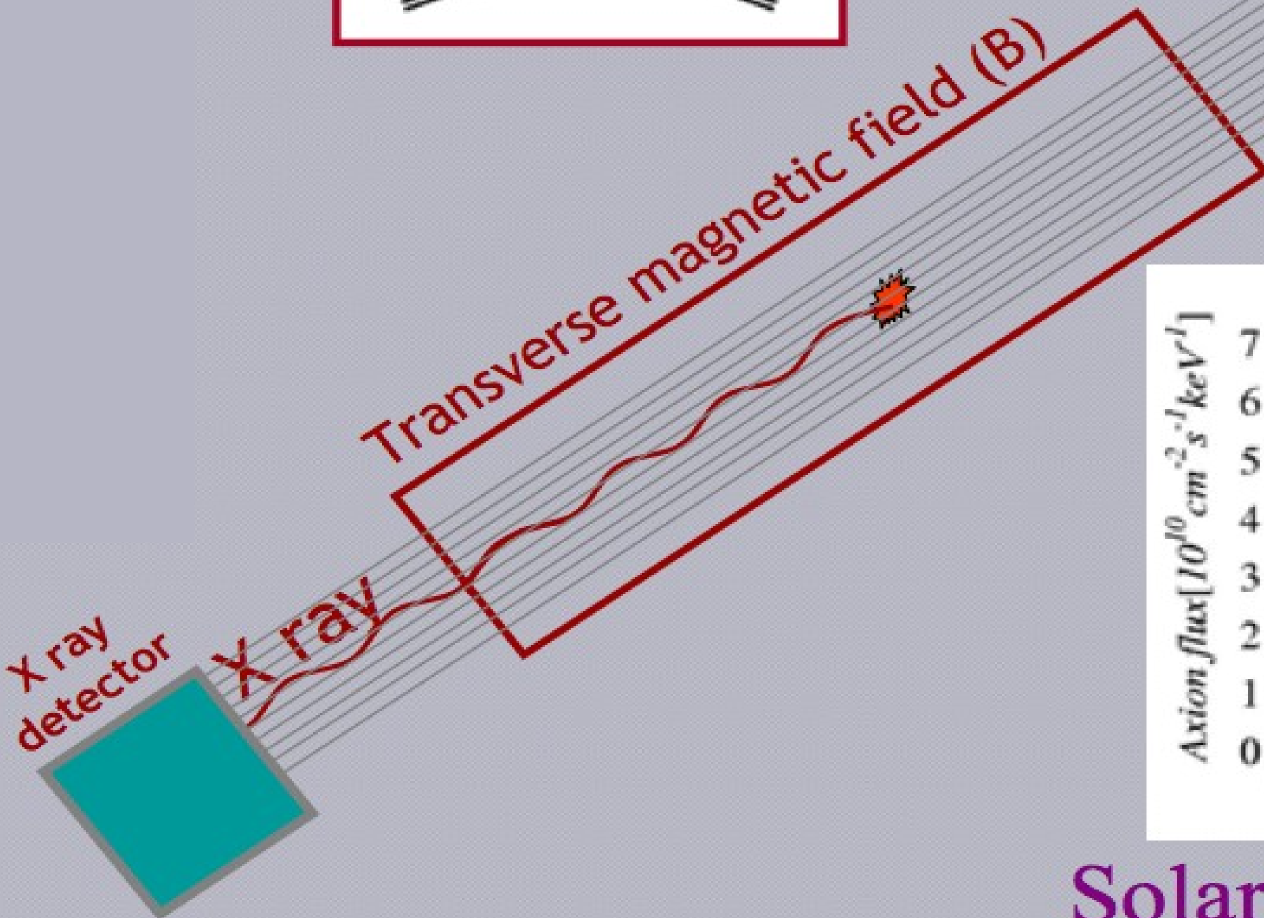
Meanwhile, at CERN ….

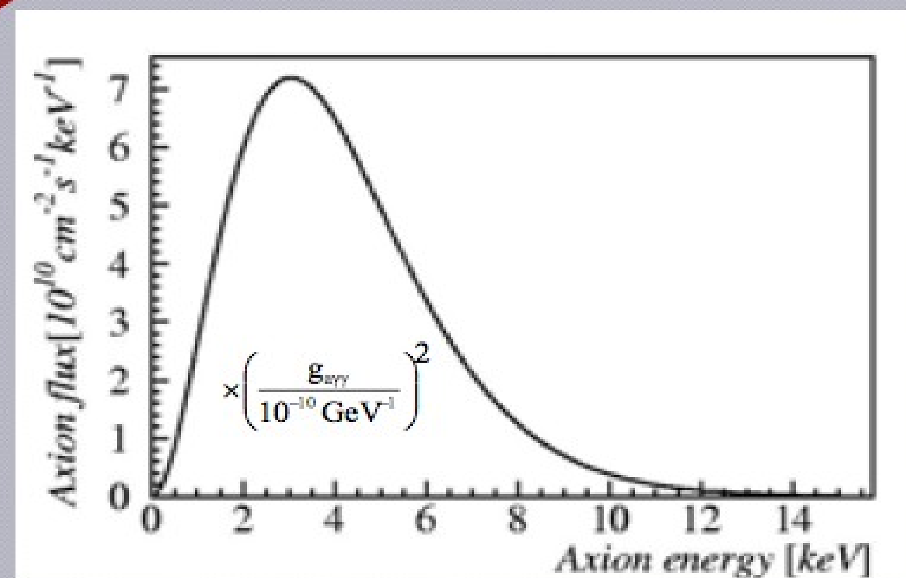
(CAST: CERN Axion Solar Telescope)

Axion-photon conversion

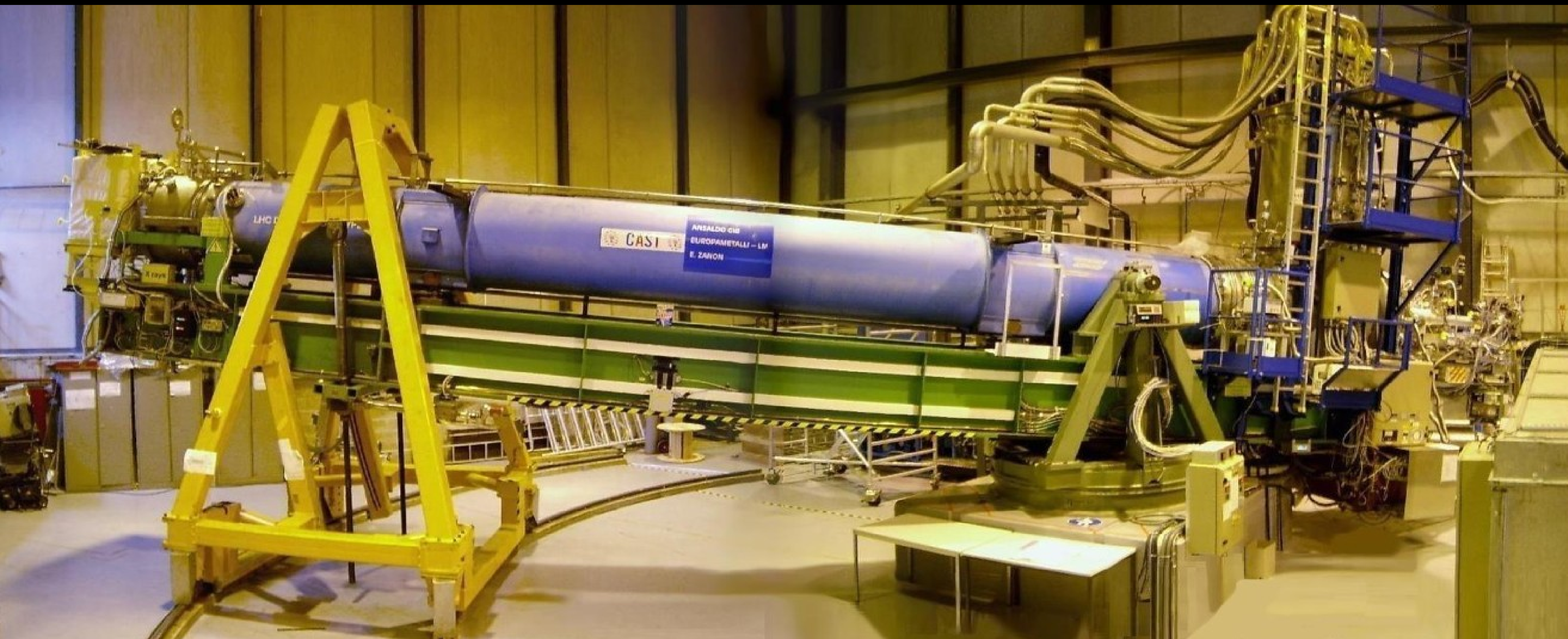








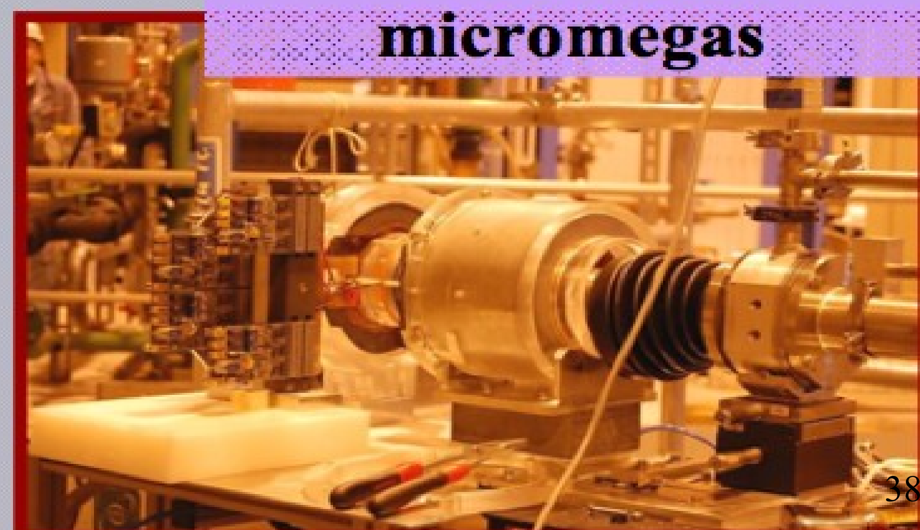
Solar axion flux on Earth



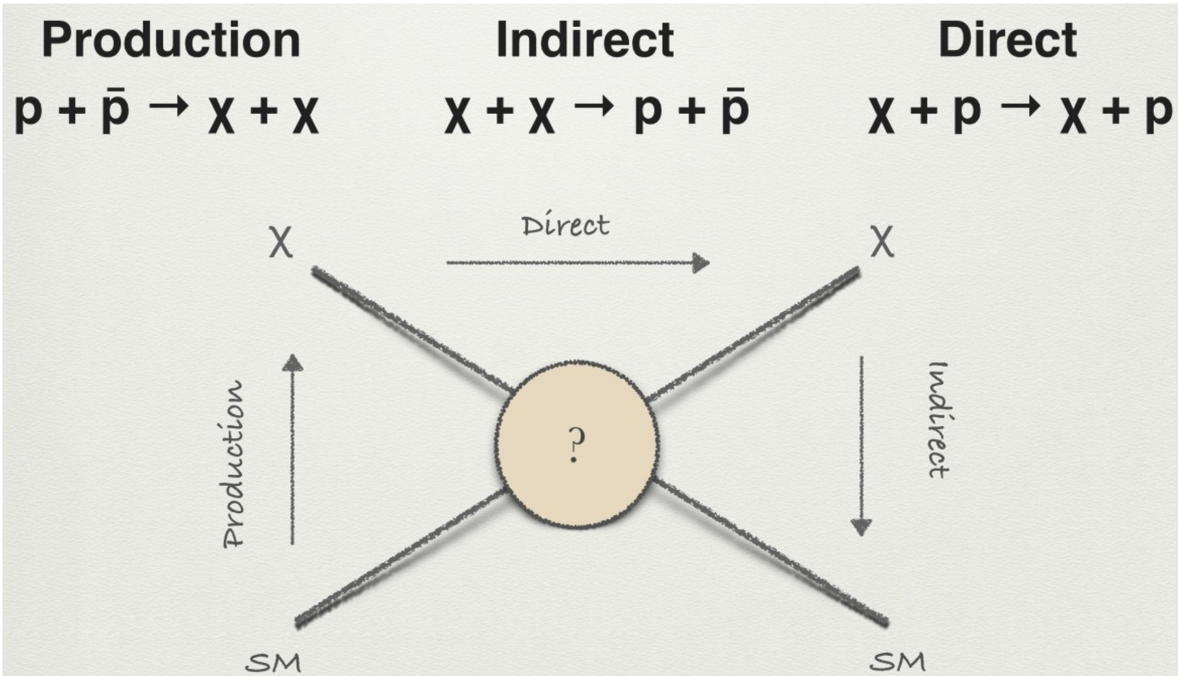
Experiment CAST at CERN

Facing "sunset axions" 2 microbulk micromegas

Facing "sunrise axions" 1 microbulk micromegas



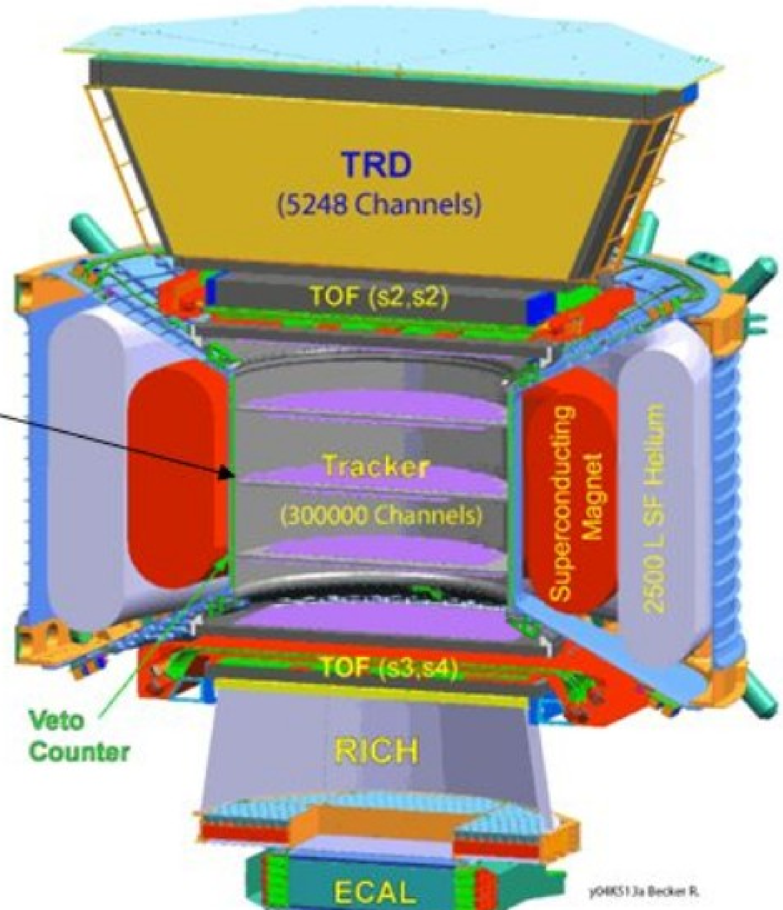
Indirect WIMP detection



AMS02 – Building Blocks

Silicon Tracker is a tracking detector and it is the core of AMS-02.

It is surrounded by the others sub-detectors or sub-systems.




AMS auf der ISS

WIMP detection: indirect detection

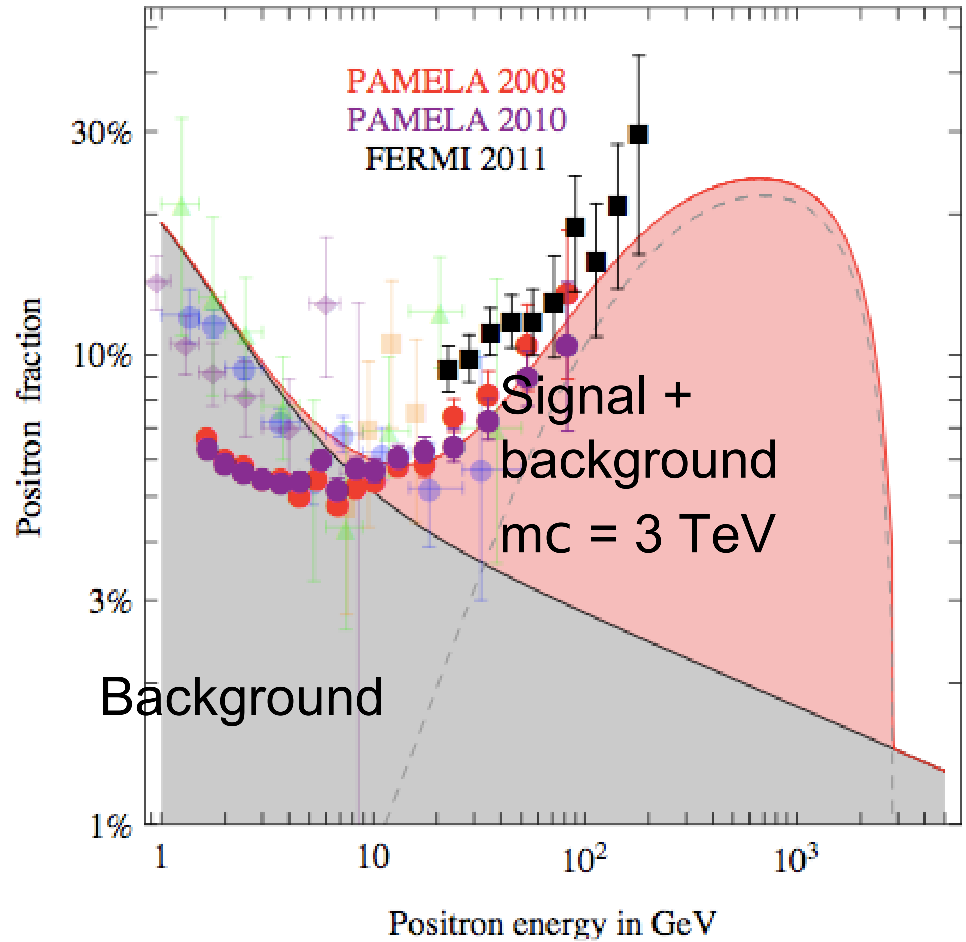
If WIMPS are neutralinos, they are Majorana particles, so c-c scattering is possible. Annihilation may produce standard model particles such as e^+e^- pairs.

$$\chi\,\chi \rightarrow e^+\, e^-$$

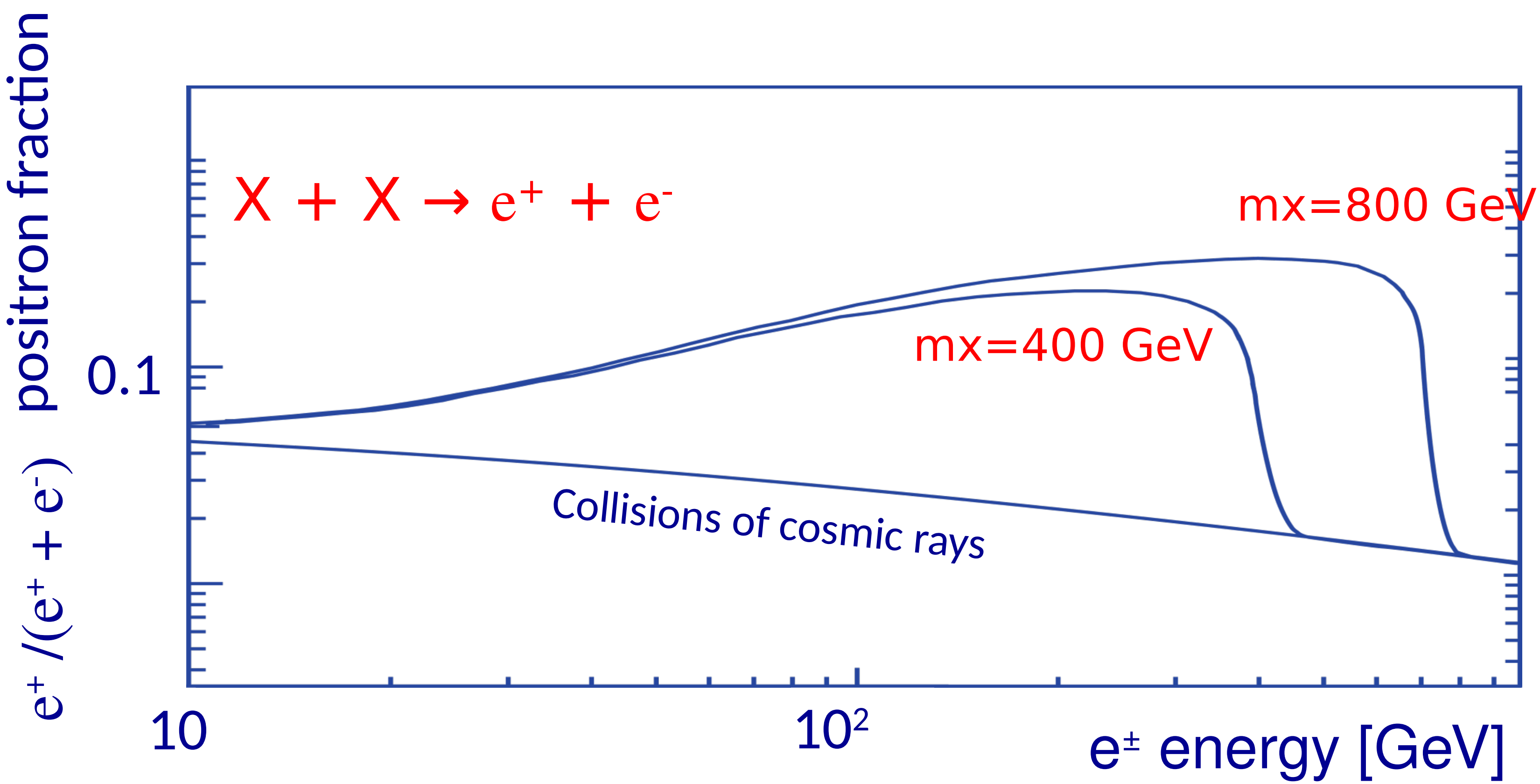
Antimatter in cosmic rays:

Satellite experiments such as PAMELA, FERMI, AMS-02 see a possible signal for positrons.

However, no signal is seen for antiprotons.

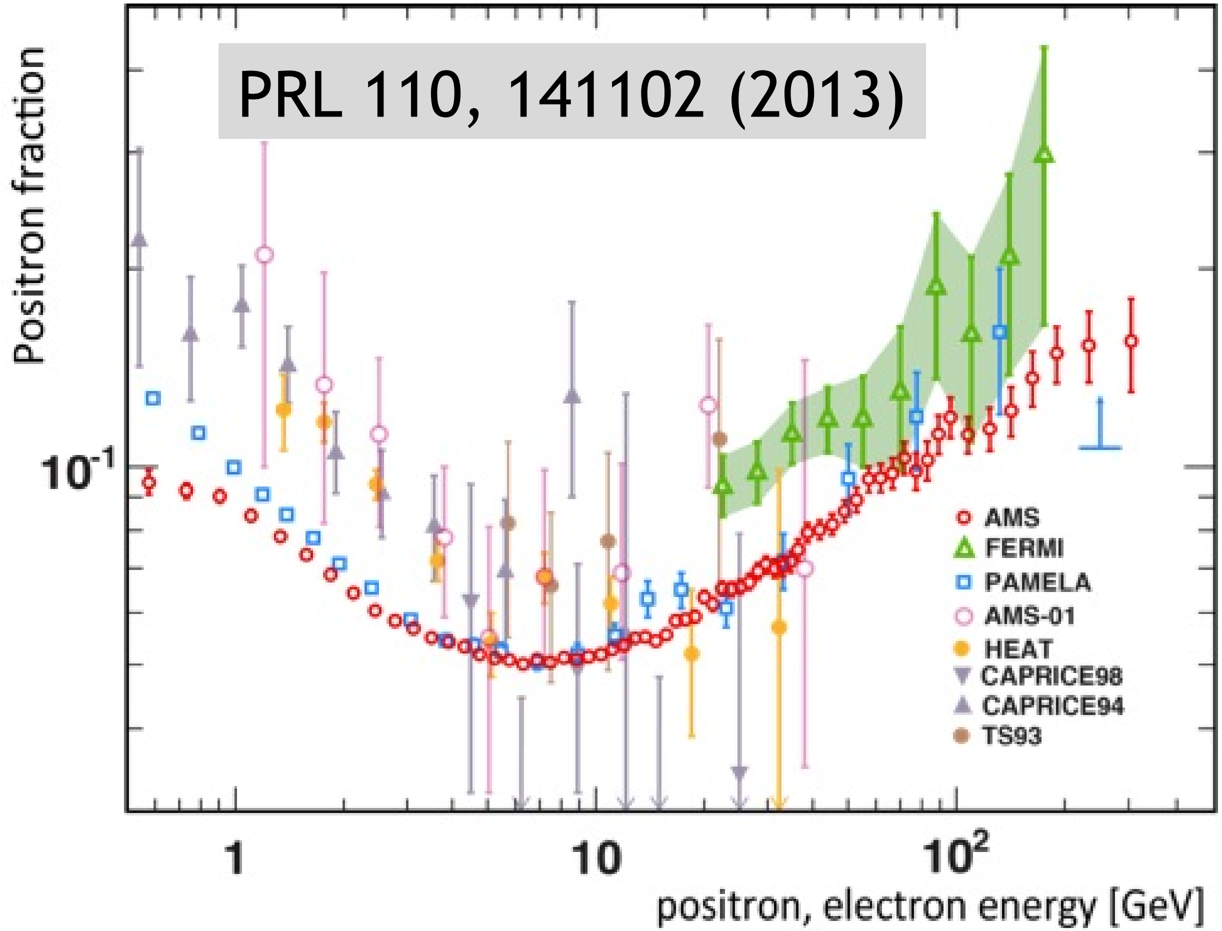


Simulation for WIMP annihilation



Model for dark matter: I. Cholis et al., arXiv:0810.5344

AMS-02 Results – April 2013



Anisotropy parameter: δ ≤ 0.036 (95% C.L.)

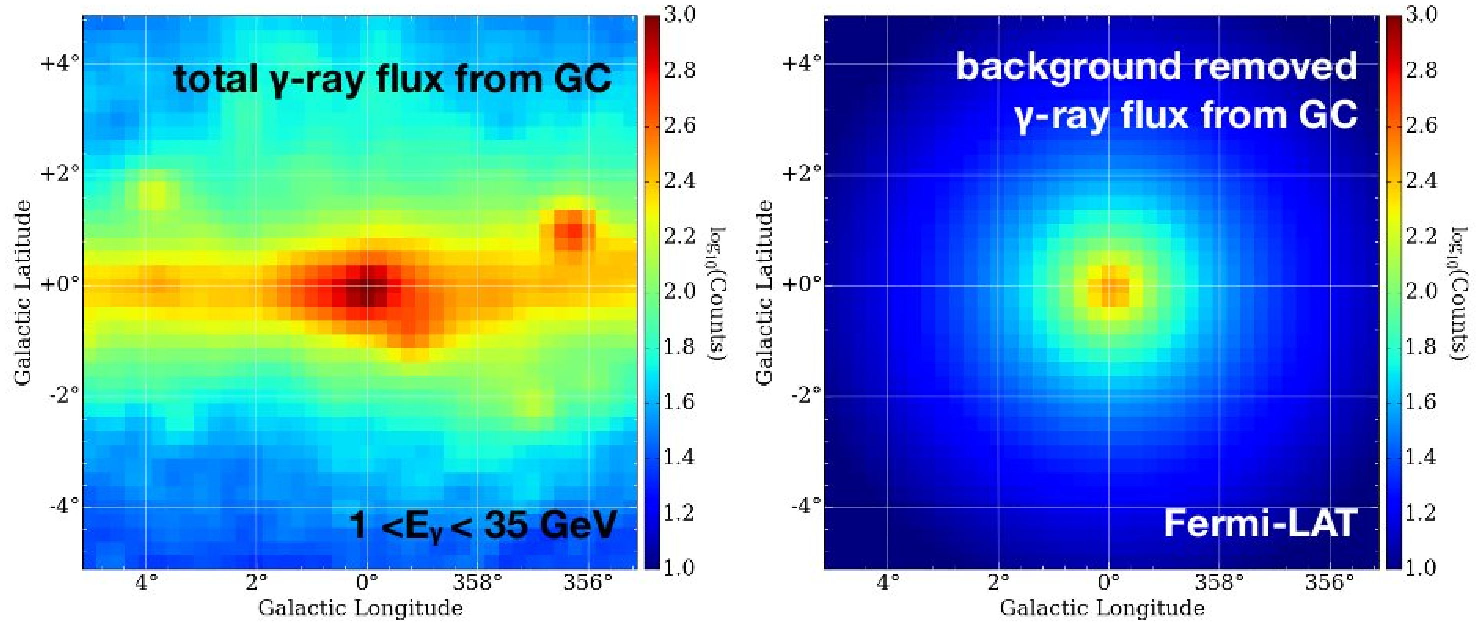
If the excess shows no anisotropy, it should have a particle physics origin (dark matter?).

$\chi\chi \rightarrow b\bar{b}$

Dark Matter γ Signal from the Galactic Center

excess of γ's ~ 1-10 GeV from the galactic center observed

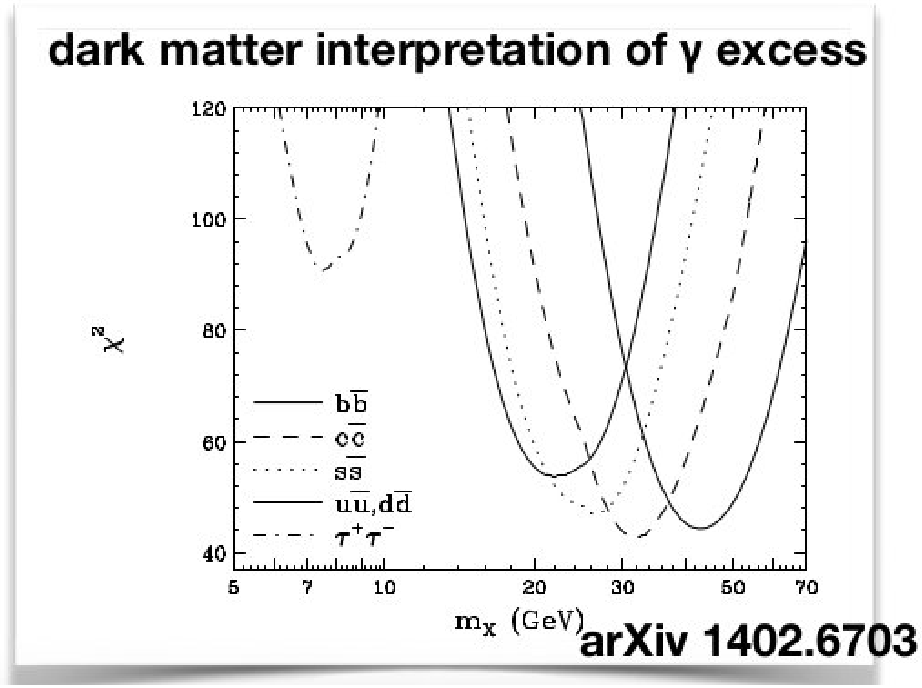
arXiv 1604.00014



- satellite based measurement with sensitivity towards lower energies
- contribution from astrophysical sources to the background model still under discussion
- excess can be interpreted as dark matter annihilation

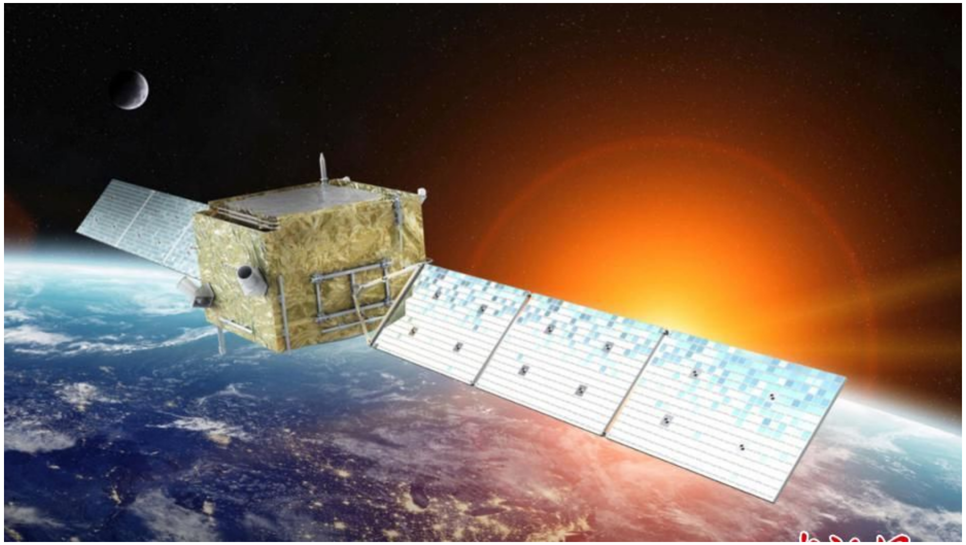
Dark Matter γ Signal from the Galactic Center

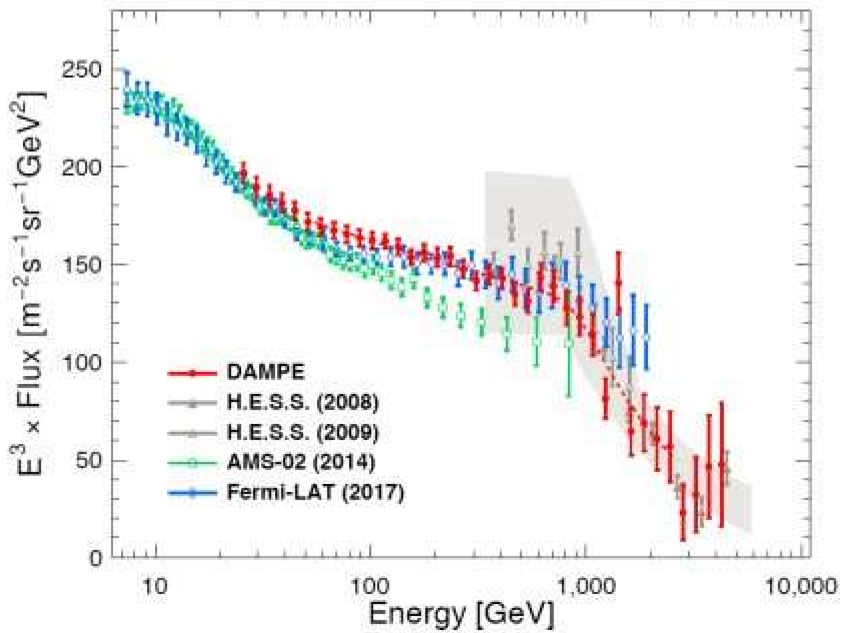
- dark matter interpretation points towards a dark matter particle with 20 GeV $\lesssim m_\chi \lesssim$ 70 GeV
- determined cross-section consistent with the thermal relic cross section $\langle\sigma v\rangle \sim 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$
- better understanding of γ emission from GC required
- confirmation by different experiment needed



Meanwhile, in China ….

DArk Matter Particle Explorer (DAMPE)





Released Nov 29th. HEPHY Journal club discussion:

Dec 15th 11 am, HEPHY Library (Nikolsdorfergasse 18)

https://indico.hephy.oeaw.ac.at/event/322/

arXiv:1711.10989

Intermediate Summary Indirect Detection

- dark matter searches using indirect methods depend strongly on astrophysical modelling / assumptions
- dark matter distribution of the source
- background contribution and signal propagation
- indirect searches provide best limits towards high-mass dark matter candidates
- no convincing signal observed yet
- a few interesting candidate signals which cannot be excluded
- 30 GeV $\lesssim m_\chi \lesssim$ 70 GeV candidate from the galactic center
- $m_\chi \sim$ 1000 GeV from positron excess in e.g. AMS-02
- Interesting results from DAMPE