DARK MATTER

Direct and indirect detection. Annual modulation effect.
Search at hadron colliders

DIPARTIMENTO DI FISICA

SAPIENZA
UNIVERSITÀ DI ROMA

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Elementary Particle Physics, Anno Accademico 2015-16

http://www.roma1.infn.it/people/rahatlou/particelle/

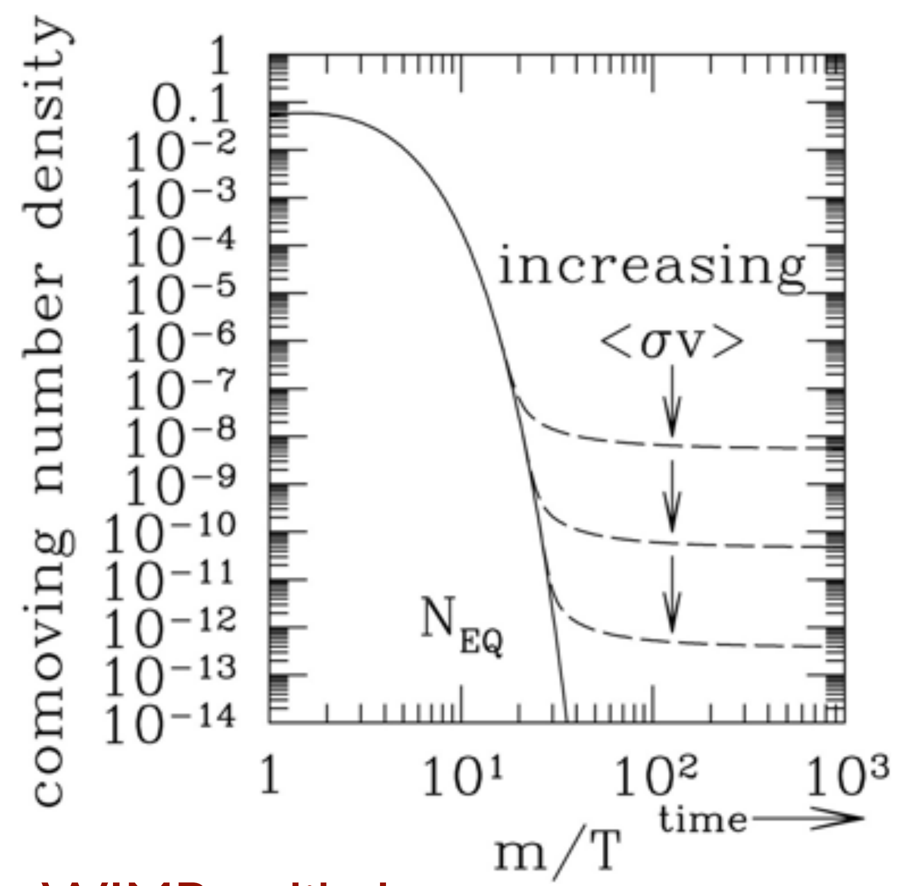
CANDIDATE DARK MATTER PARTICLES

- Properties
  - long lived (old)
  - non-relativistic (slow)
  - no electric or color charge
  - very weak interaction with Standard Model particles
  - subject to gravity interaction

- Several potential candidates fulfilling these requirements for dark matter
  - Dark: weakly interacting with electromagnetic radiation
  - Hot & dark: ultra-relativistic velocities
    - neutrinos
  - Warm & dark: very high velocity
    - sterile neutrinos, gravitinos
  - Cold & dark: moving slowly
    - Lightest SUSY particle (neutralino, gravitino as LSP), Lightest Kaluza-Klein particles
  - Nonthermal relics:
    - Bose-Einstein condensate (BEC), axions, axion clusters, solitons, supermassive wimpzillas

Weakly Interacting Massive Particle (WIMP)

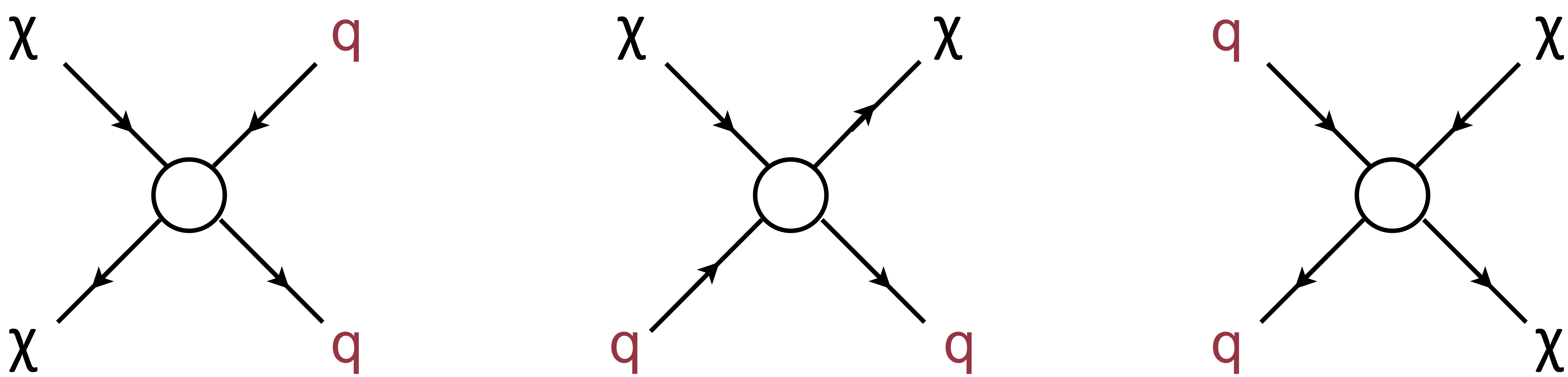
- Possibly a new particle with a mass at weak scale
  - produced abundantly in the Big Bang
  - Only subject to gravity and weak interactions
  - large mass compared to known SM particles



- Expansion of the Universe and decreasing temperature affects WIMPS
  - lower temperature(energy) of the universe means less energy for production of WIMPs
    - when temperature below WIMP mass production of new WIMP unlikely
  - expansion of the Universe reduced the WIMP density
    - smaller density implies smaller cross section for interaction between WIMPs
  - At some point density and temperature so low that WIMP number does not change (WIMP "freeze-out")
- Relic density measured by their interaction strength
  - inversely proportional to the annihilation cross-section
  - measured relic density today: 0.3 GeV/cm^3

DARK MATTER INTERACTION

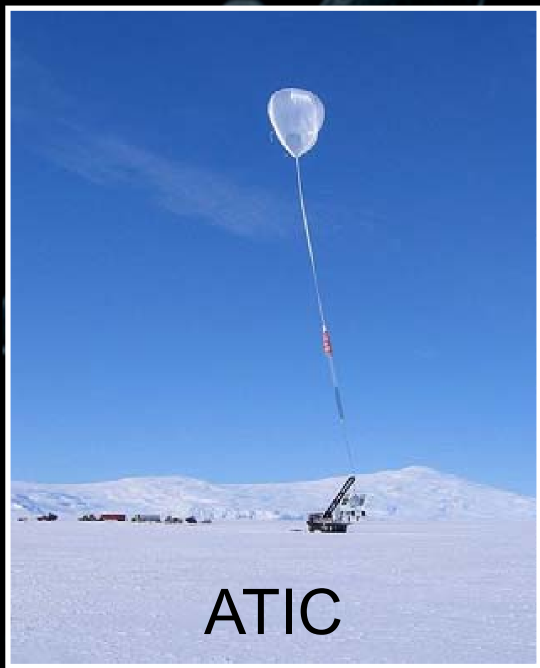
- Exact interaction of DM with ordinary matter determines relic abundance

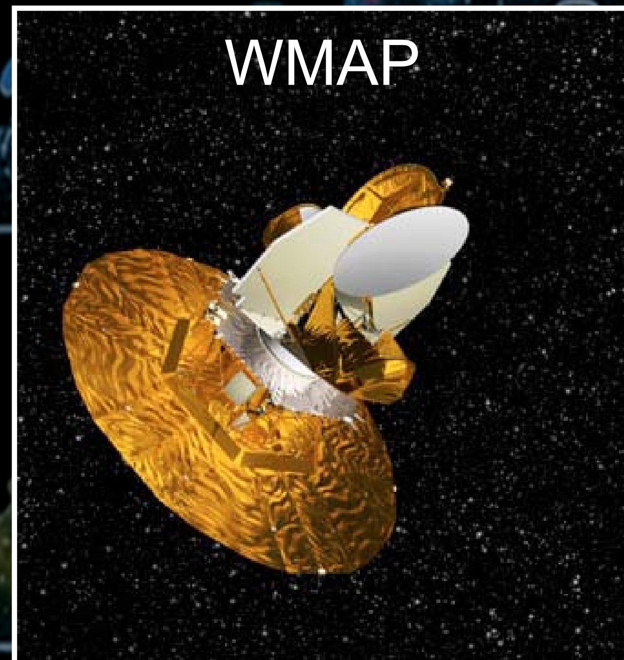


Indirect Detection *Direct Detection* *Production at Colliders*

- Different experimental technique and detectors for each approach

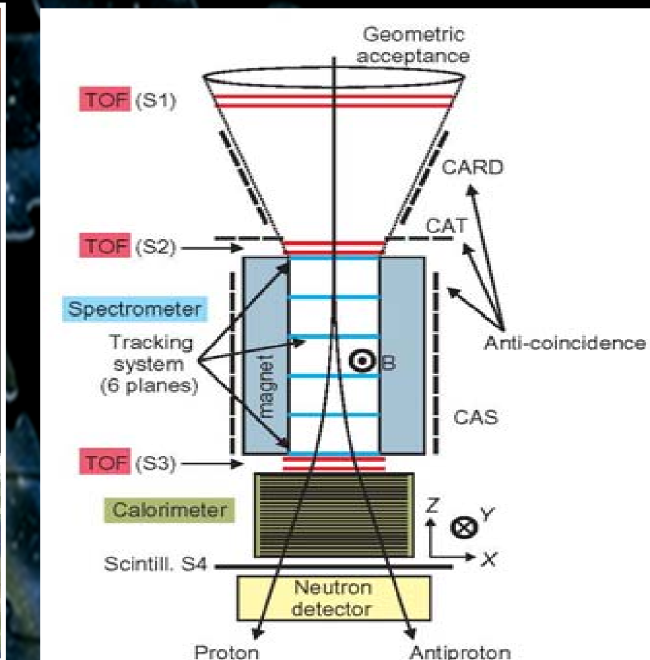
Indirect Detection

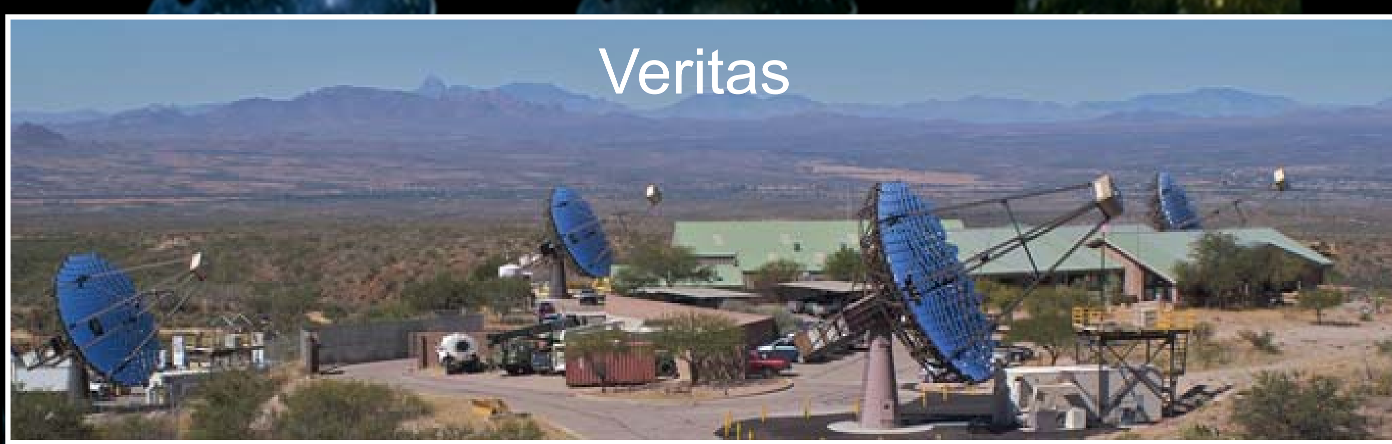

ATIC


WMAP


Fermi/GLAST

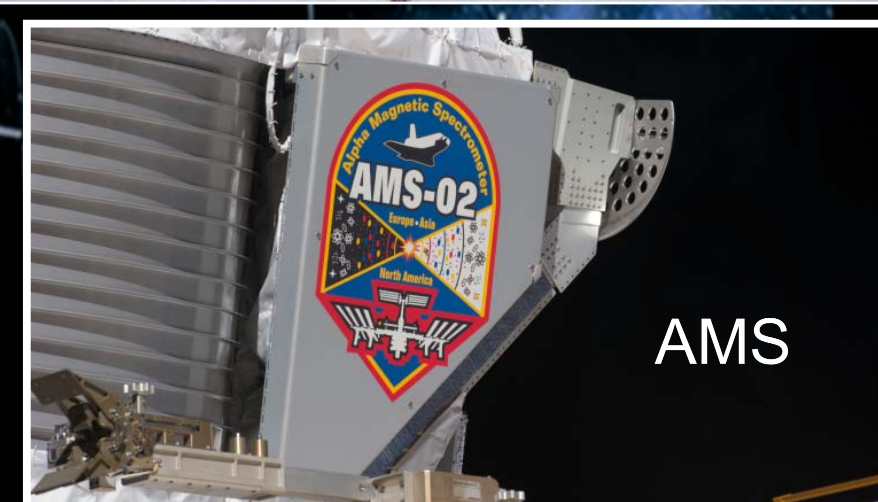
PAMELA




Veritas


IceCube

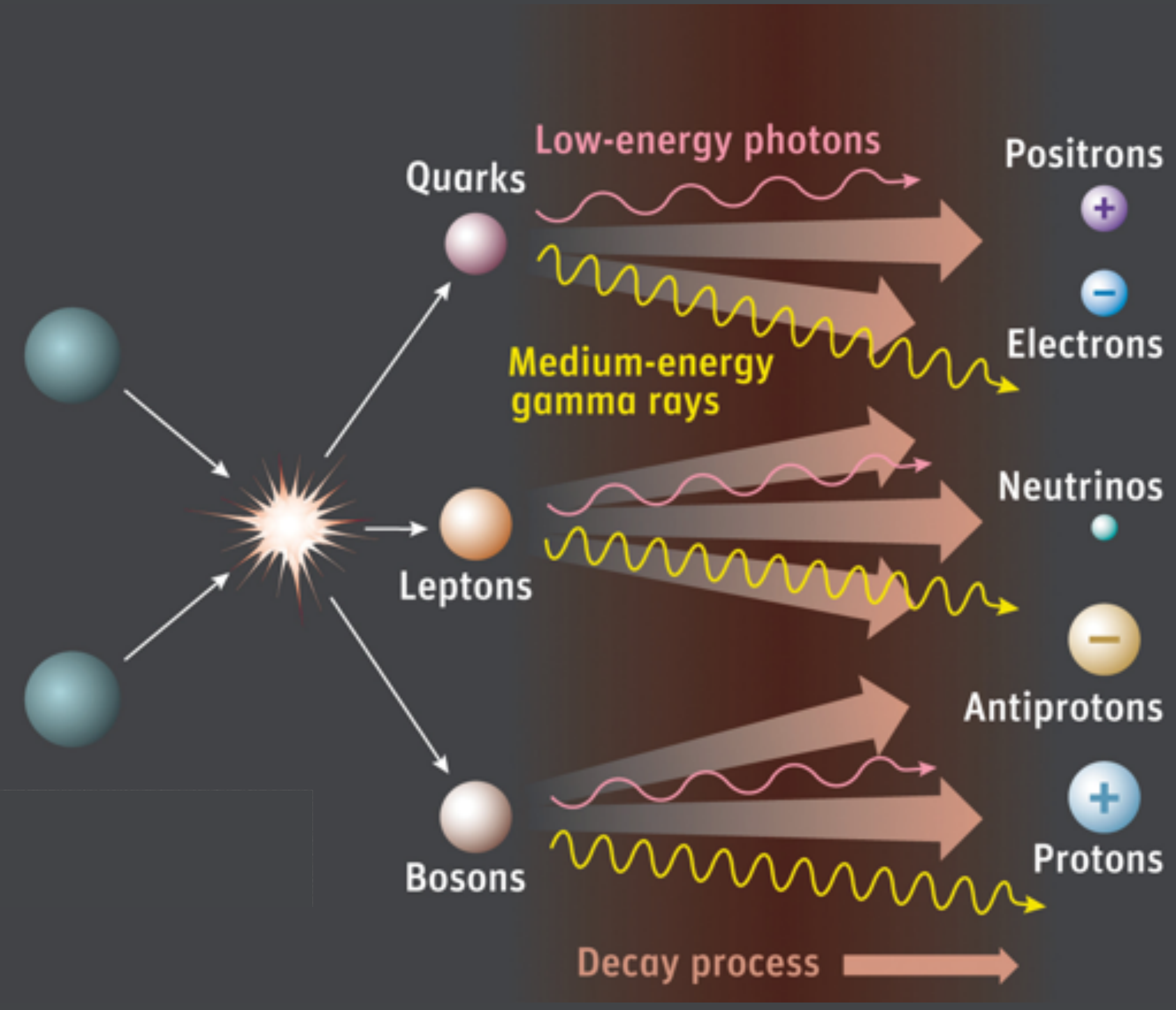

H.E.S.S.



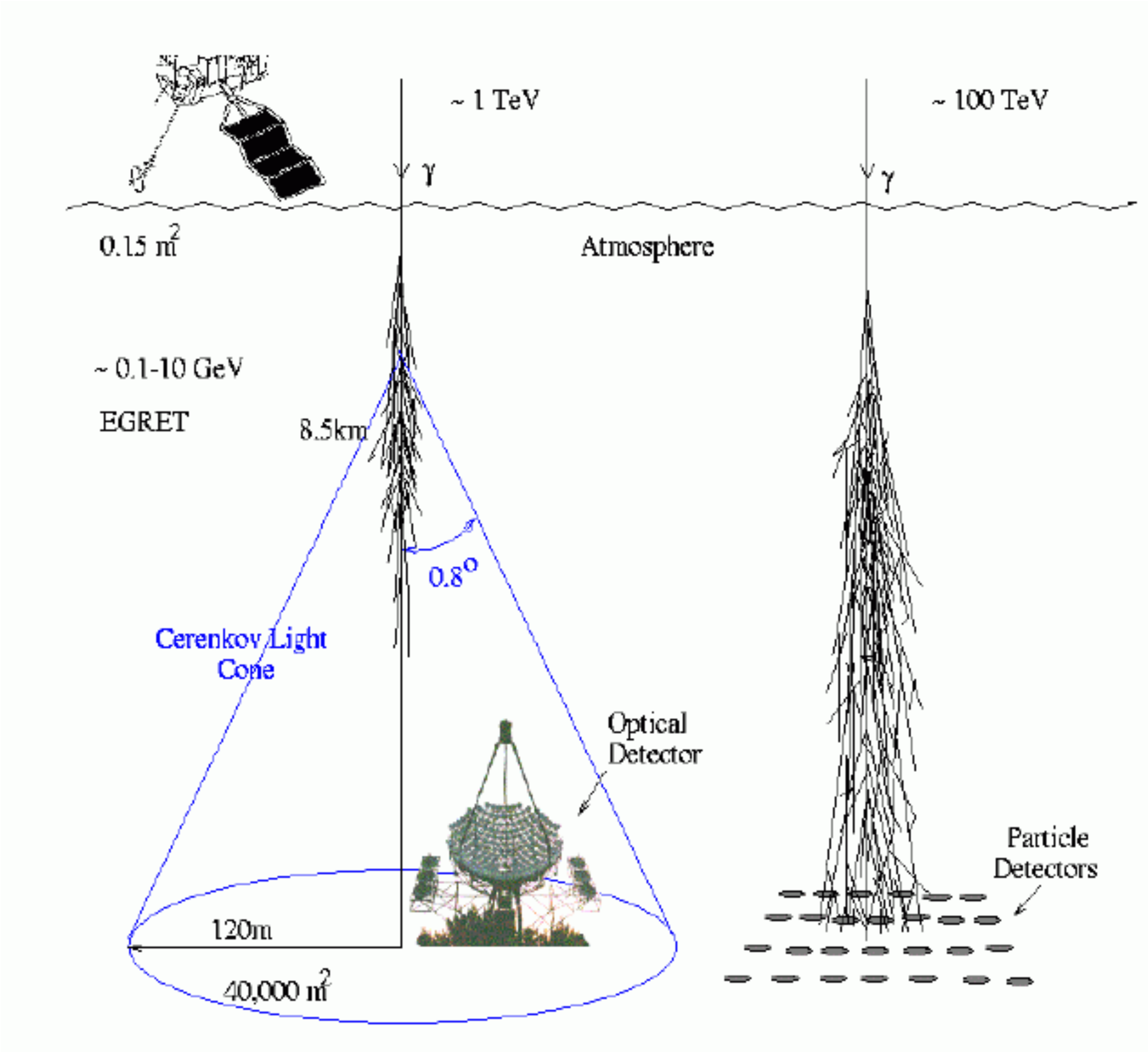
AMS

INDIRECT DETECTION

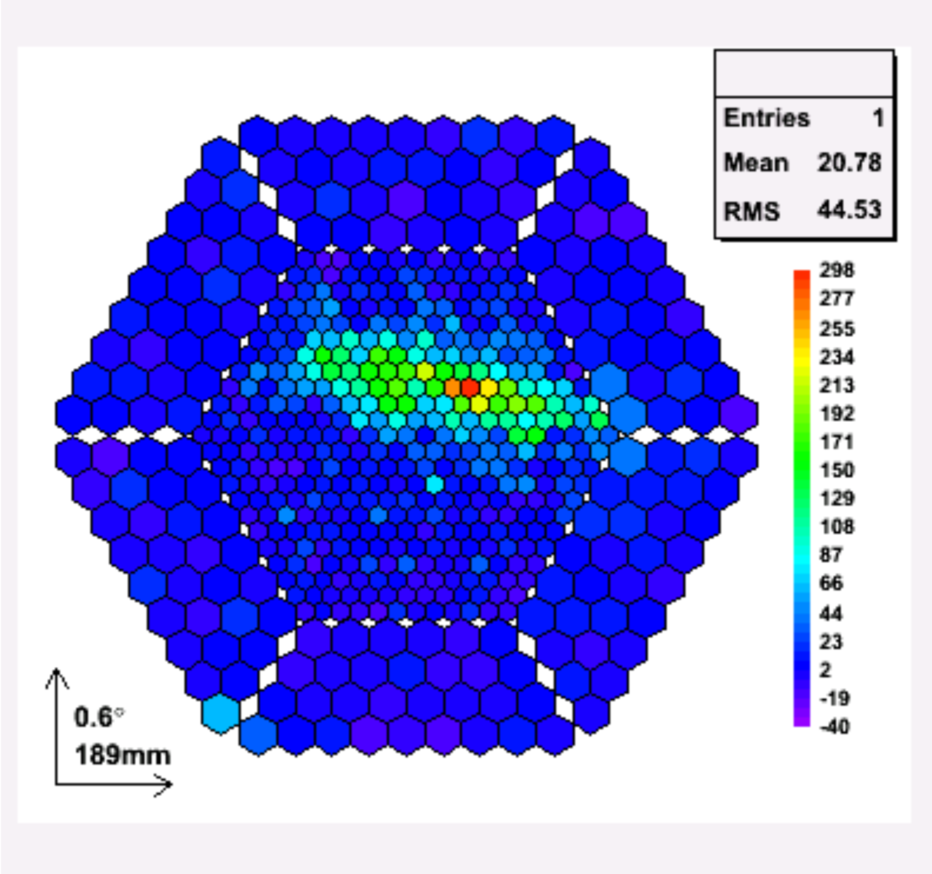
- Annihilation in high energy photons, particle-anti-particle pairs
- search for ultra-relativistic objects produced in galactic halo
  - observatory on earth or with satellites



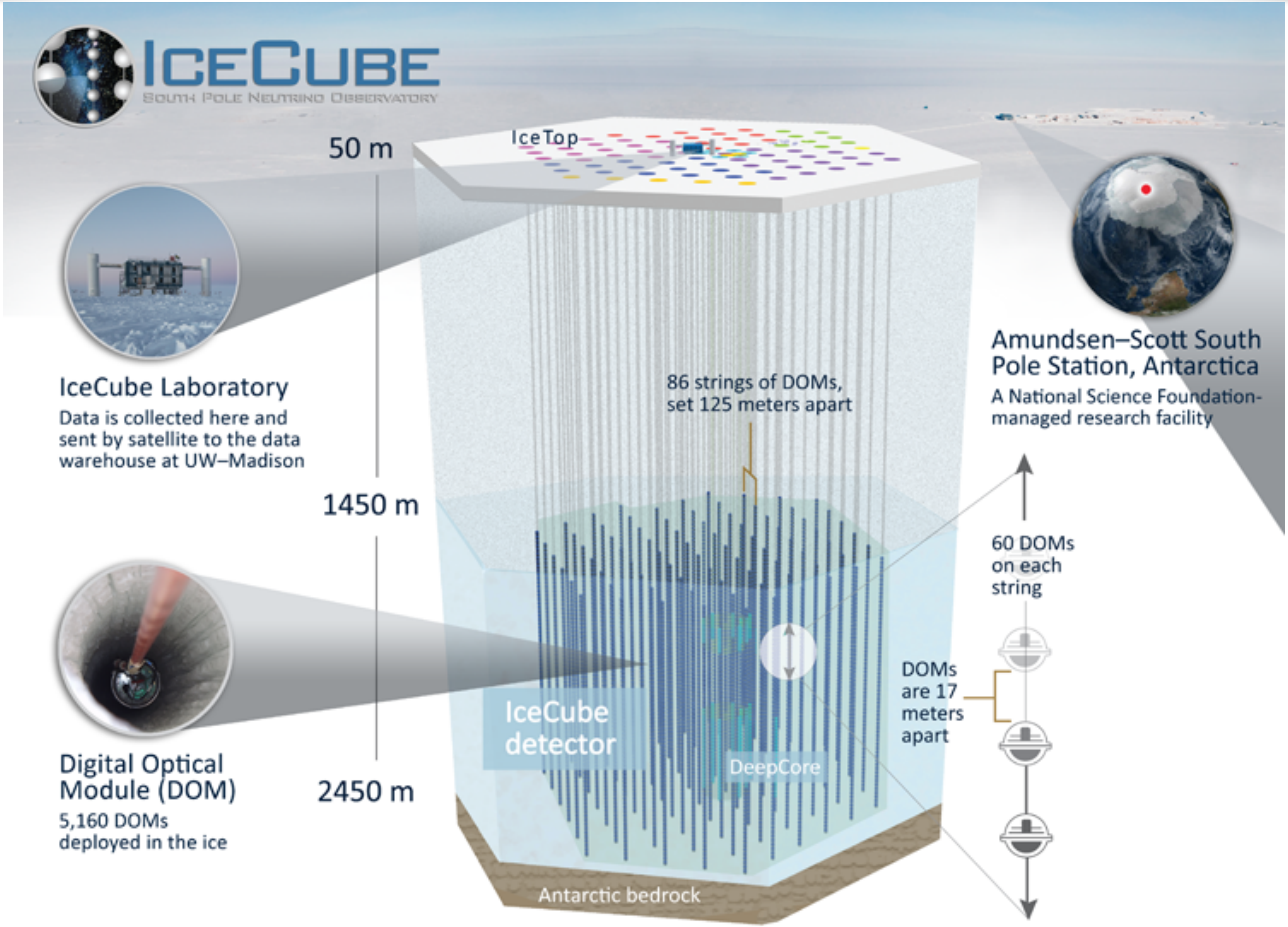
EARTH-BASED DETECTION



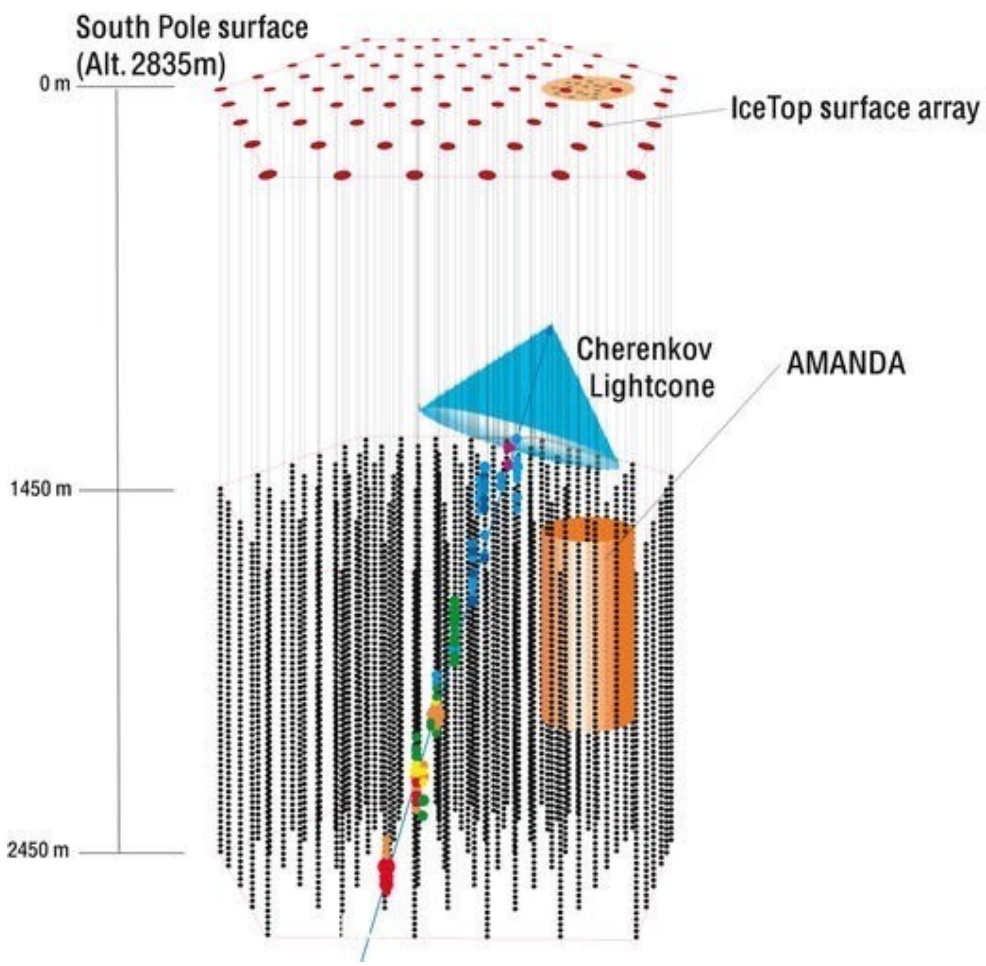
CHERENKOV SHOWER

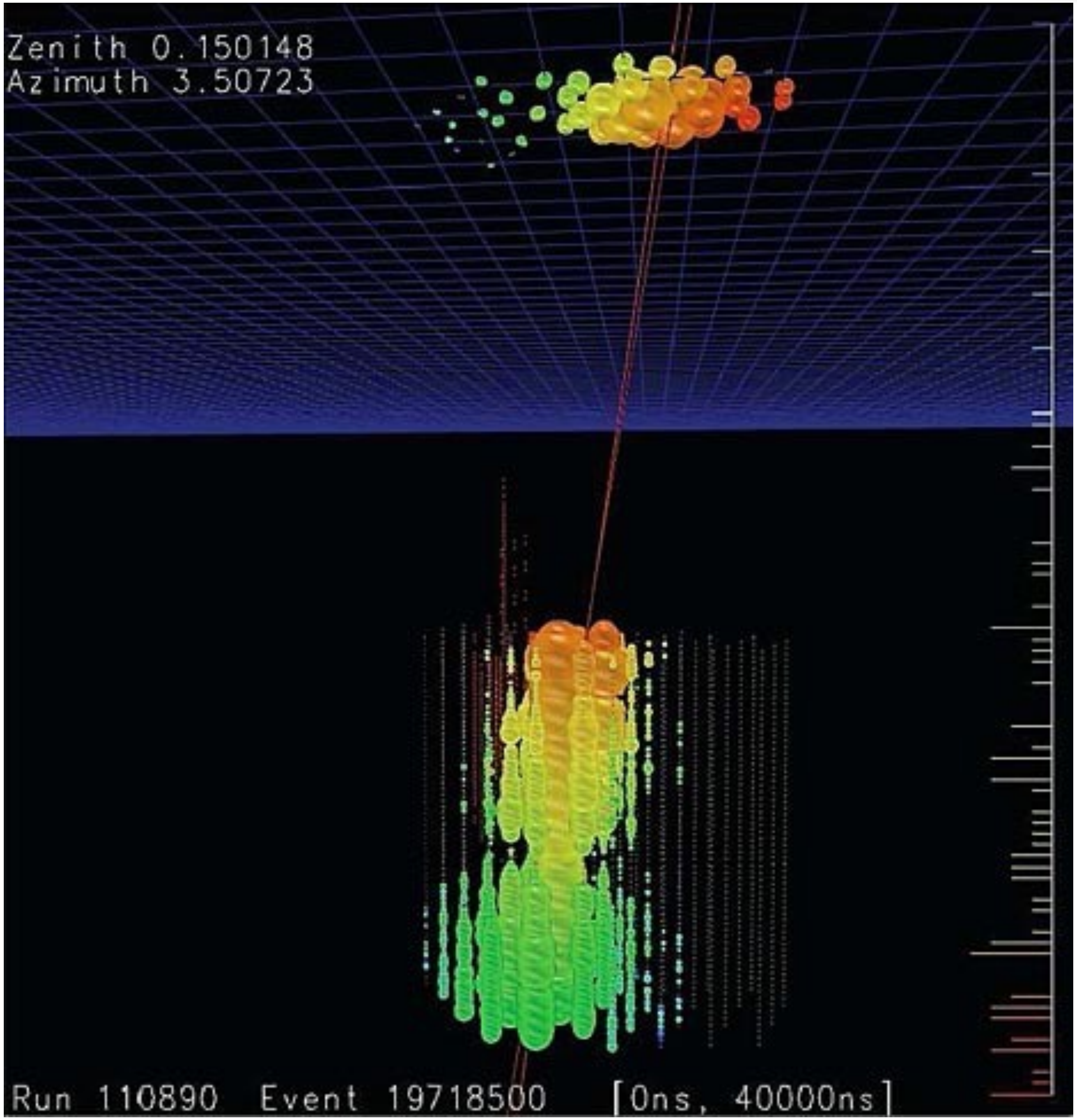


ICE CUBE


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
Antarctic bedrock

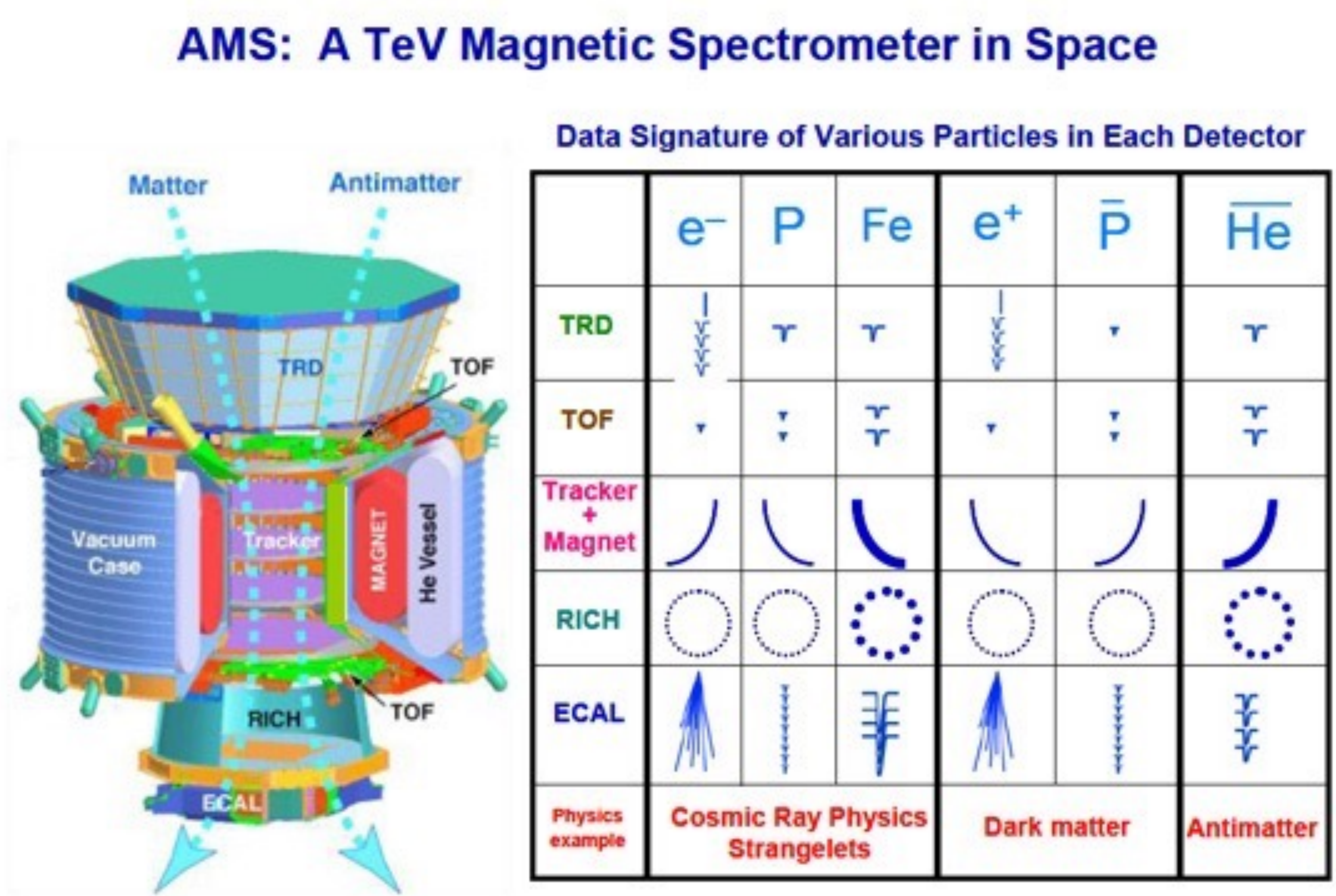
ICE CUBE EVENT





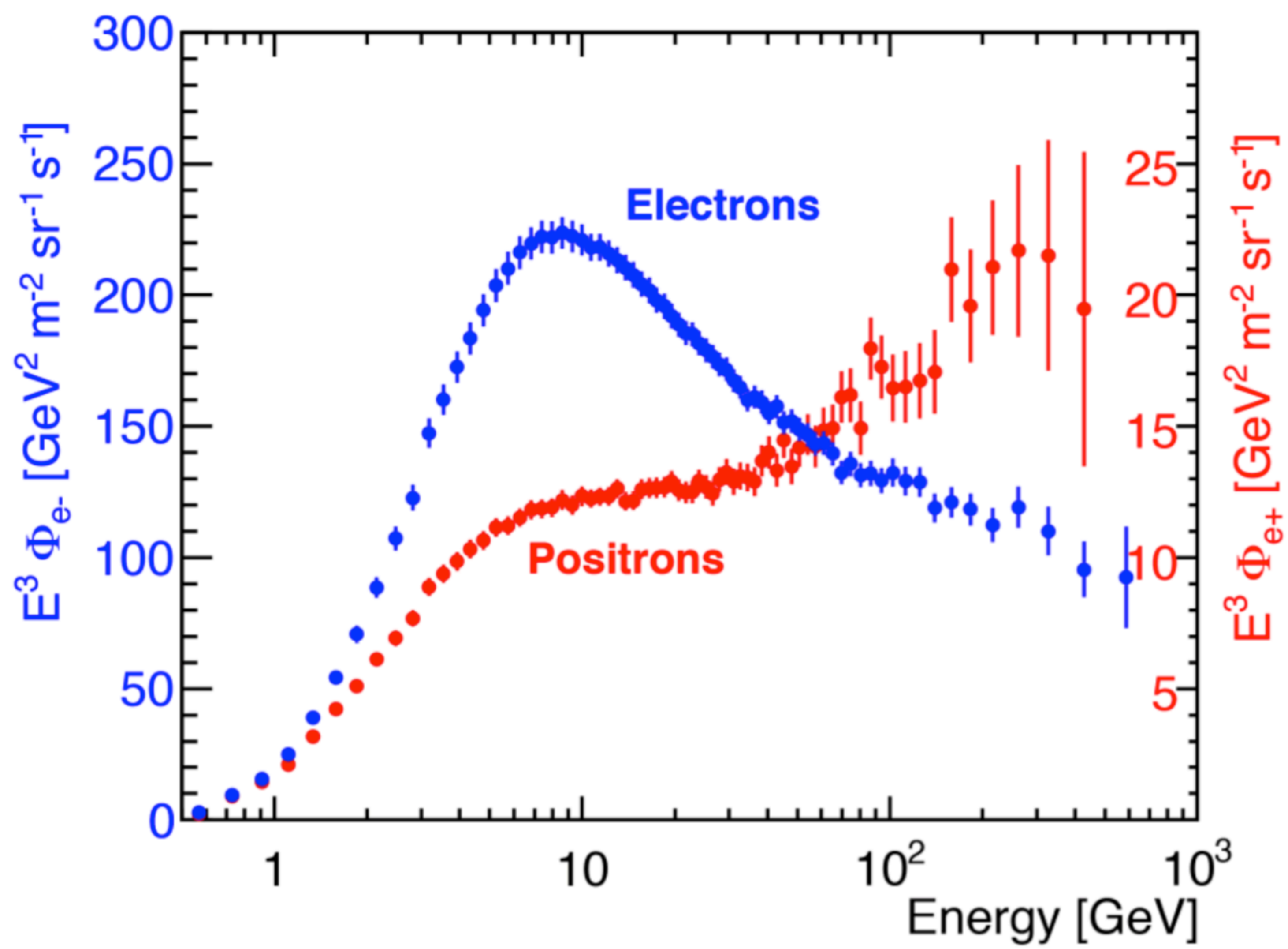
AMS @ ISS

SPECTROMETER IN SPACE



AMS Results

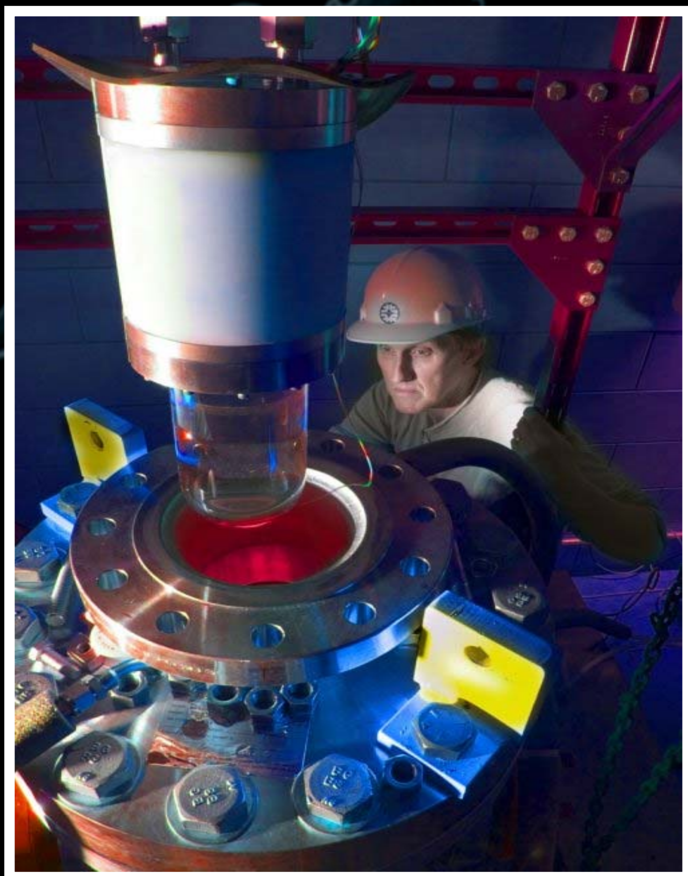
- Electron Flux and the Positron Flux significantly different in their magnitude and energy dependence
- A single power law cannot describe both fluxes
- Both spectra consistent with a charge symmetric and time independent source term with a cutoff at E_s=540 GeV
- AMS will be able to extend measurements to TeV scale



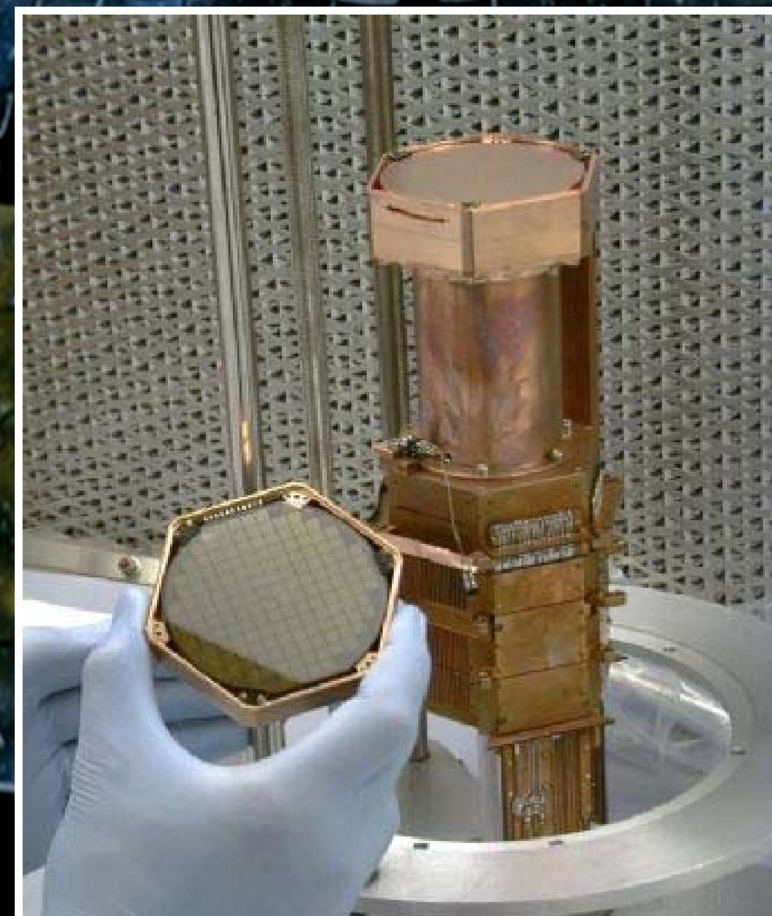
- *Dark matter identification requires*
  - Measurement of e+, e-, p ,-bar fluxes
  - Precise knowledge of cosmic ray fluxes

DIRECT DETECTION

COUPP



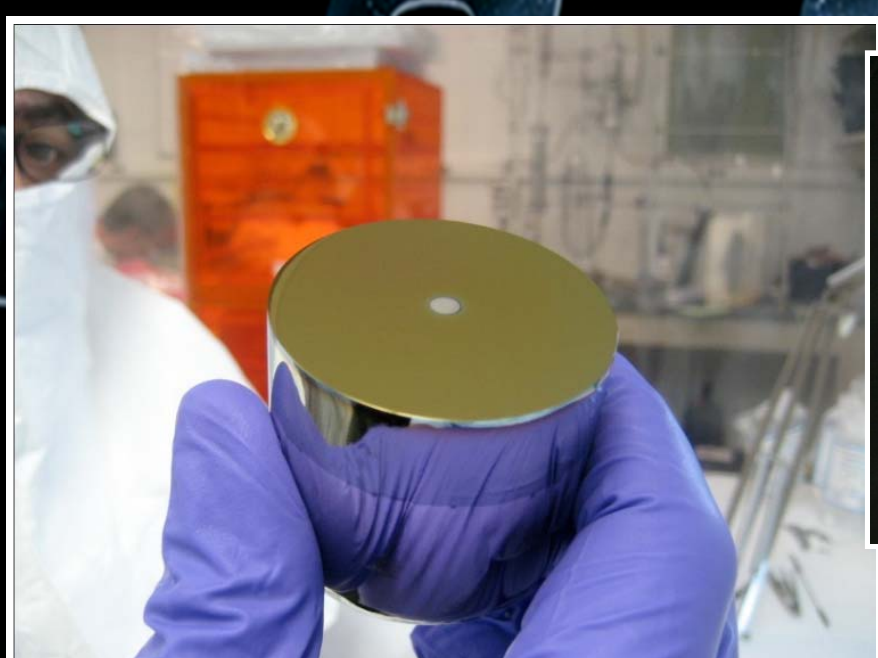
CDMS

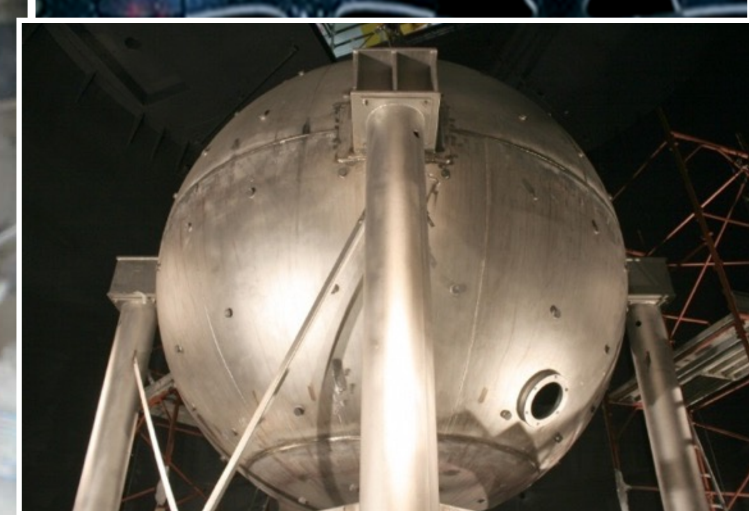


CRESST

DAMA

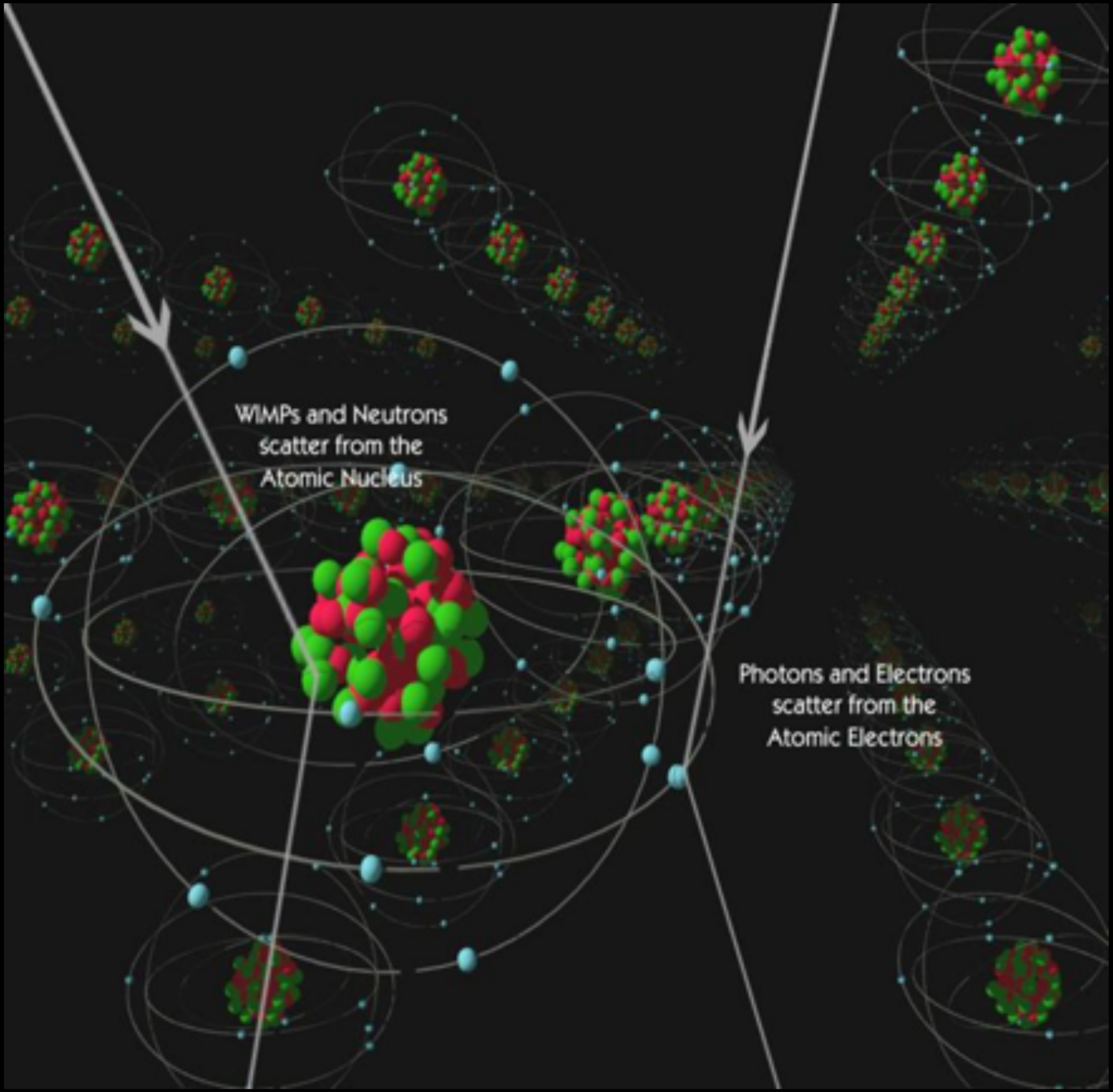
CoGeNT





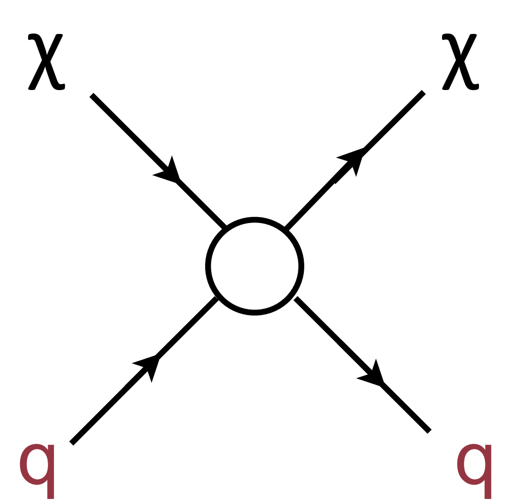
Darkside

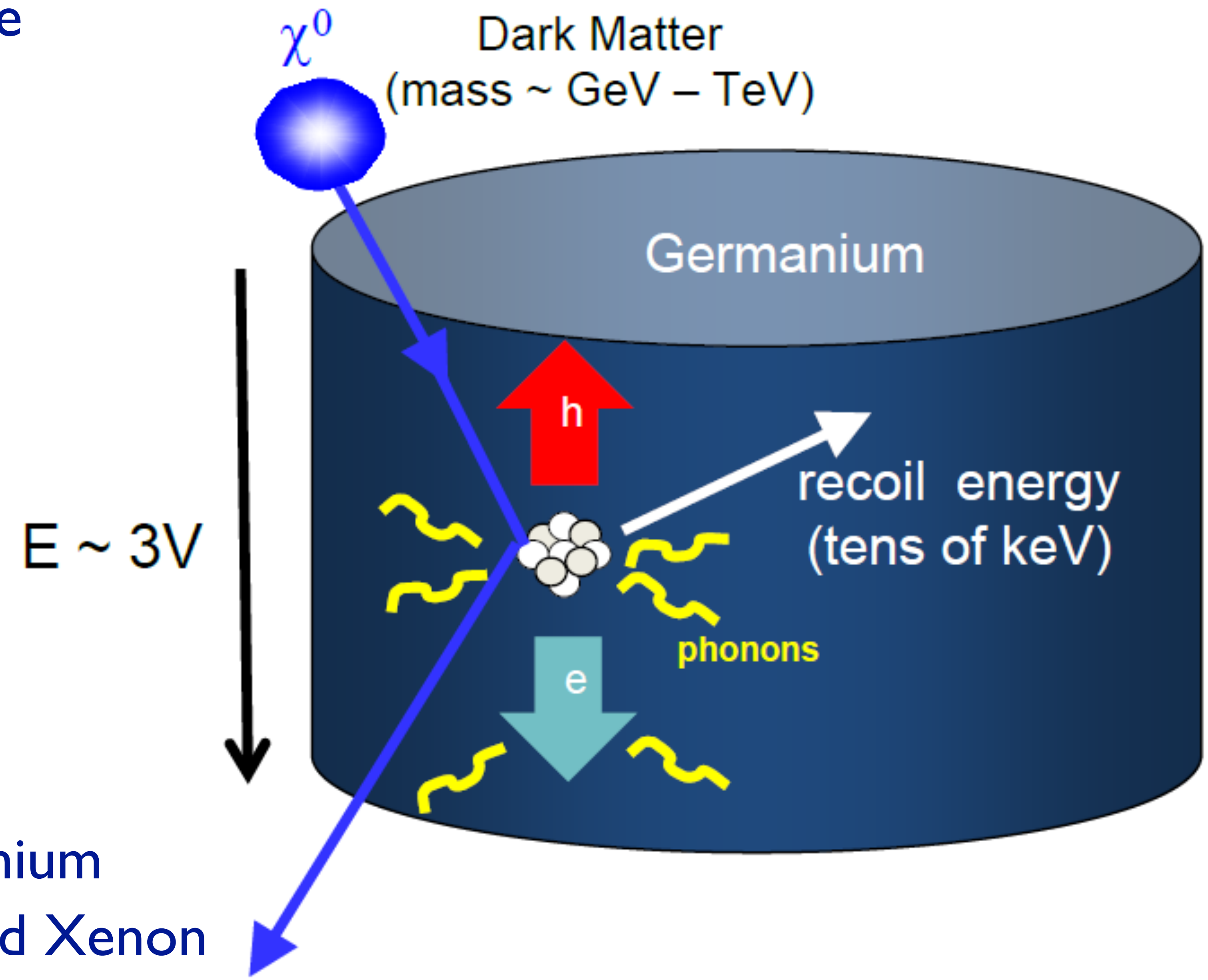
DIRECT DETECTION



DIRECT DETECTION

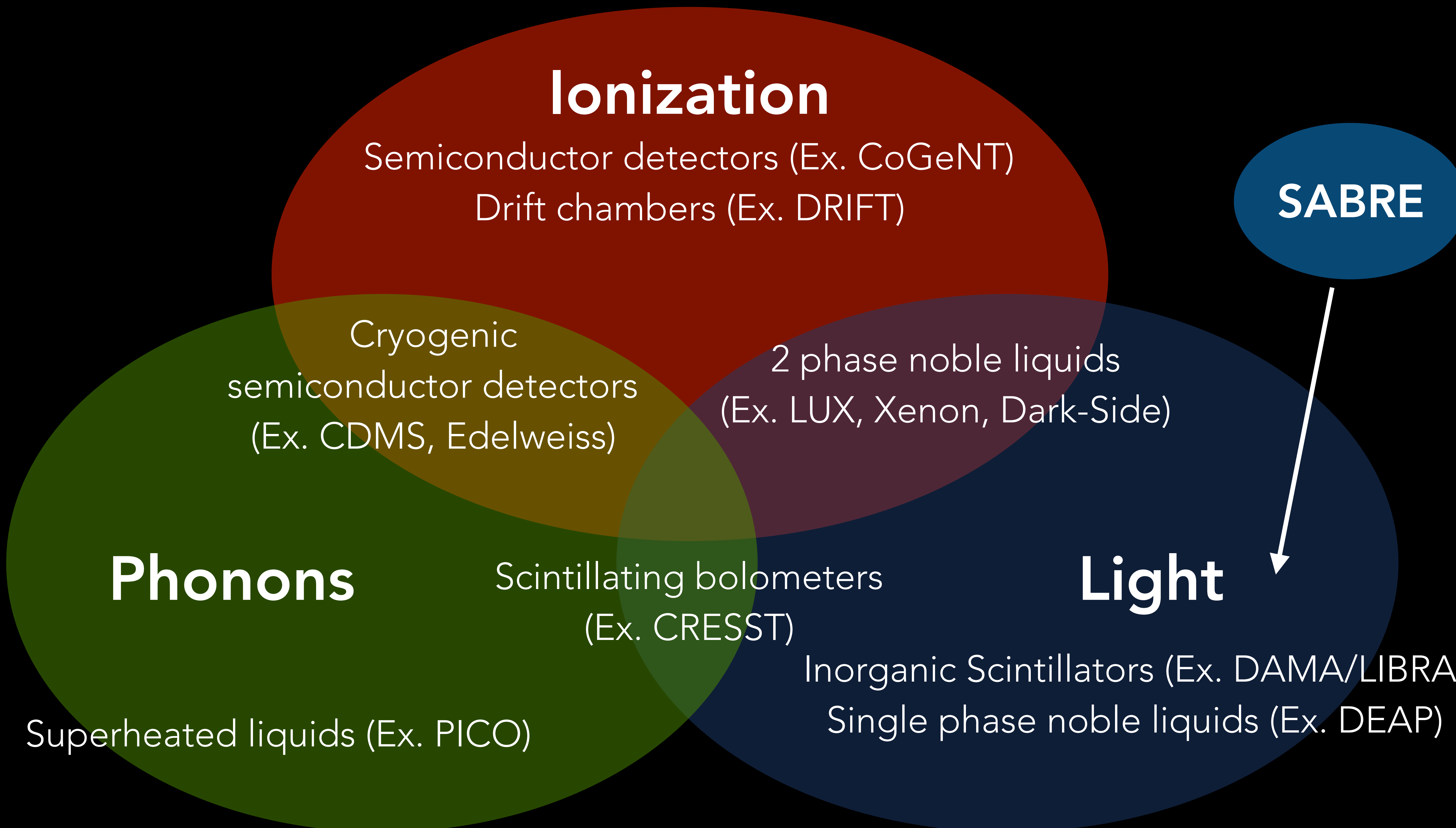
- Observe recoil of dark matter from nucleus
  - Extremely sensitive, extremely difficult... extremely successful!
  - Limited by threshold effects, energy scale, backgrounds
  - Low mass region not accessible



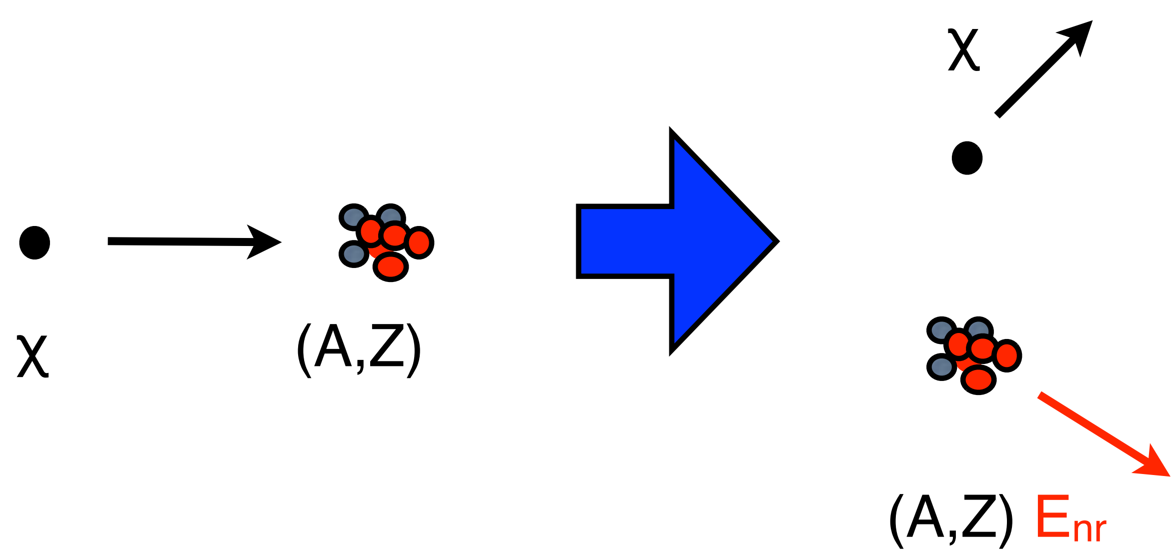


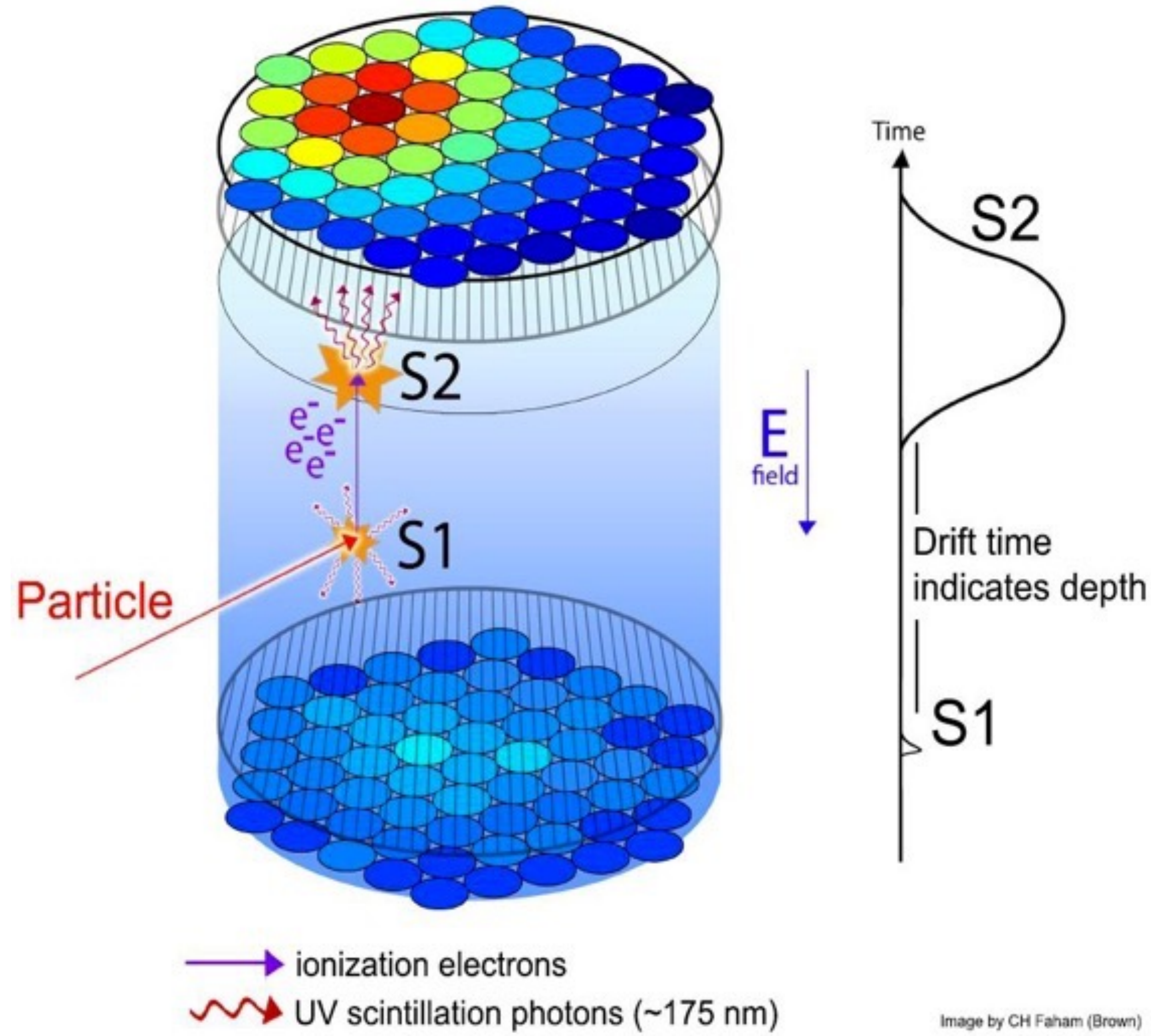
– Detection techniques
  - Heat, vibration: silicon, Germanium
  - Light: NaI, CsI, Liquid Argon and Xenon
  - Charge: Germanium, silicon,

DETECTION CHANNELS



DETECTION PRINCIPLE





- For m_χ = 100 GeV and A = 100:
  - $\sigma_{SI} = 10^{-42}$ to 10^{-44} cm^2
    - depends on assumption on spin-dependence of interaction
  - Rate = 10^{-2} to 1 events/(kg day)
  - E_{nr} = 0 to 25 keV

DM Rate Estimation

$$\boxed{\frac{dR}{dE_{nr}}} = \frac{1}{2\mu_\chi \mu^2}\sigma(q)\rho_\chi \boxed{\eta(v_{min}(E_{nr}), t)}$$

$$\eta(v_{min}, t) = \int_{v>v_{min}} dv^3 \frac{f(v,t)}{v}$$

Elastic scattering off nuclei,
E_{nr} : nuclear recoil energy

v_{min} = minimum WIMP velocity that can result in a recoil E_{nr}

- Rate depends on
  - DM parameters
    - μχ (mass)
    - σ (cross section, Spin dependent (SD) or spin independent (SI)
  - Astrophysical parameters
    - ρX (DM density)
    - f(v) (DM velocity distribution)
  - Target nucleus parameters
    - μ (reduced mass DM-nucleus),
    - A (Atomic number)

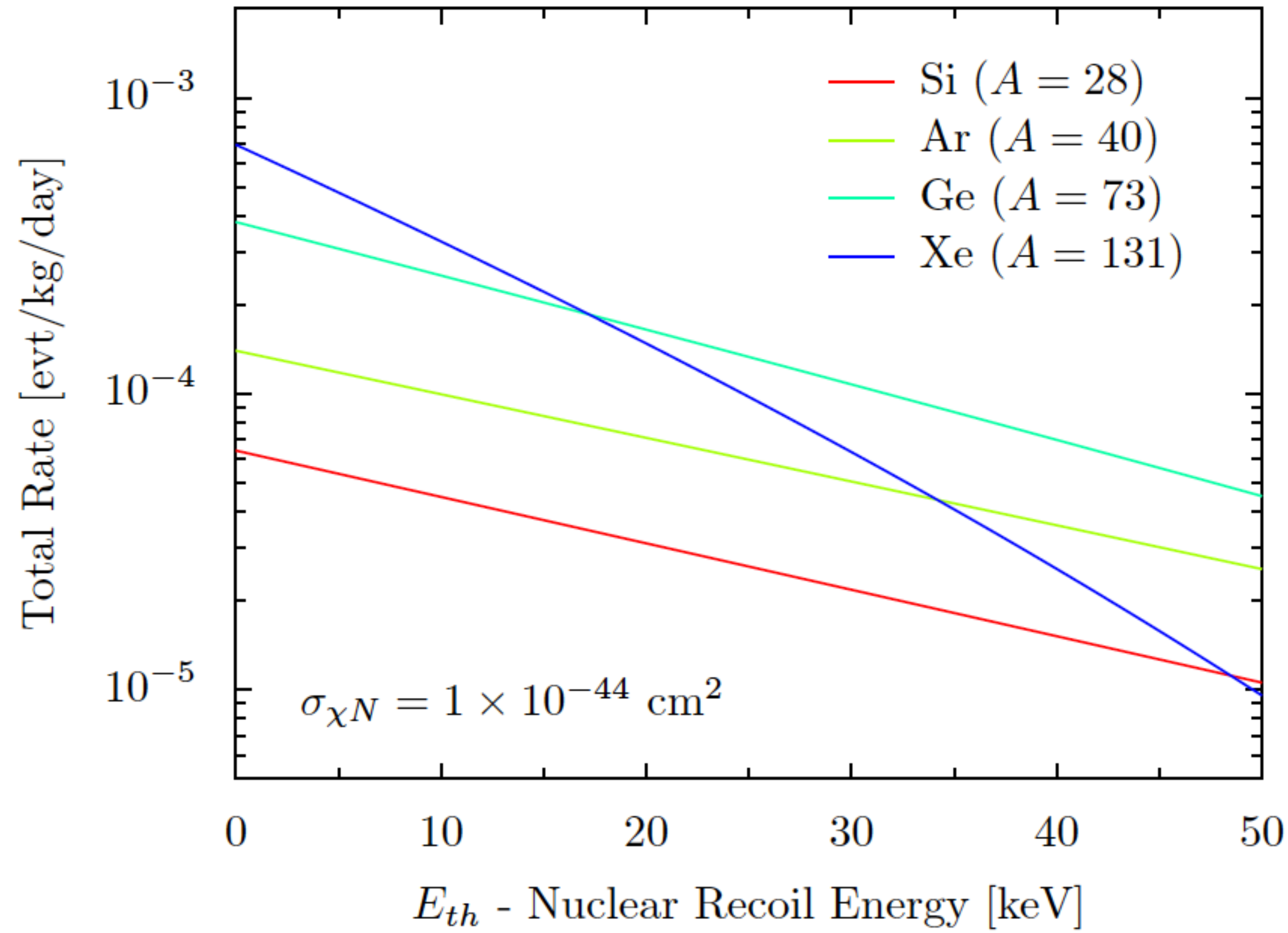
DM EVENT RATE

For μ_χ = 100 GeV and A = 100:

- $\sigma_{SI} = 10^{-42} - 10^{-44}$ cm^2
- Rate = 0.01 - 1 cpd/kg
- E_{nr} = 0 - 25 keV

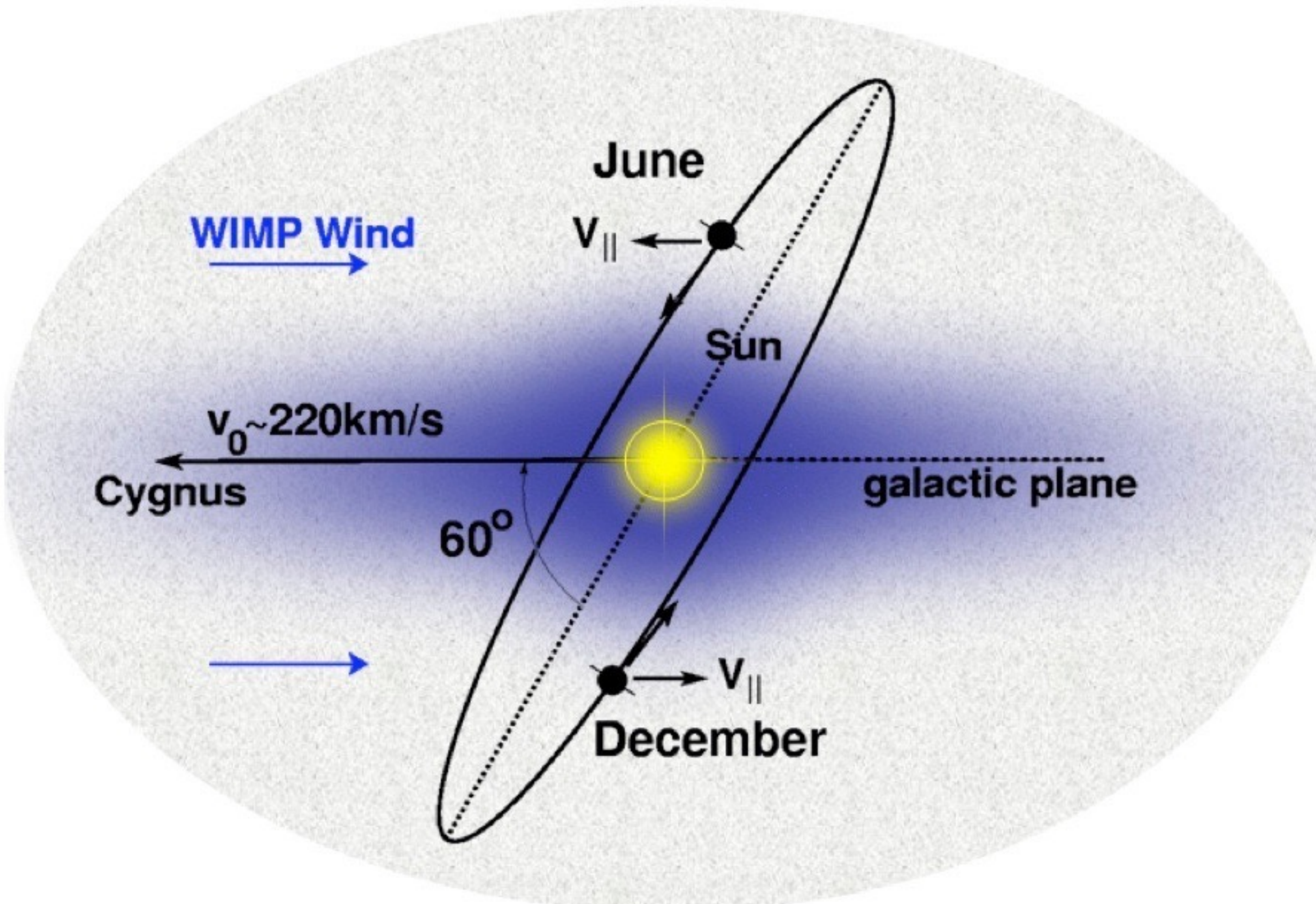
$E_{nr} = (\mu^2 v^2/M)(1-\cos\theta)$

$\mu = mM/(m+M)$



- Exponential-like shape, increasing at low E (similar to many backgrounds)
- Demands O(keV) thresholds and backgrounds close to zero
- All experiments operated in low radioactivity environments and deep underground

DARK MATTER HALO



- WIMP flux on Earth: ~10^5 cm^{-2}s^{-1} (M_X=100 GeV, for 0.3 GeV/cm^3)
  - Cross section ~ 10^{-44} cm^{-2}
- Use Large detectors for a long time
  - N_{events} = flux x time x size x cross section

Annual Rate Modulation

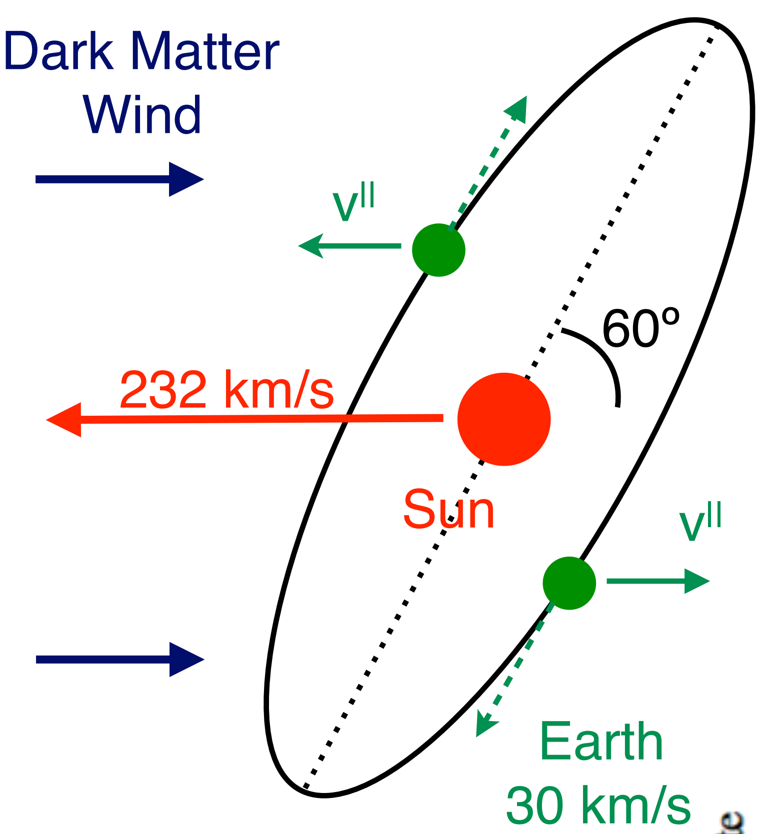
Earth velocity combines to solar system velocity in the galaxy.

Dark matter "wind" in the heart rest frame is modulated:

$$v(t) = v_{\text{sun}} + v_{\text{orb}}^{||} \cos[\omega(t - t_0)]$$

and affects the counting rate:

$$S(E,t) = S_0(E) + S_m(E) \cos[\omega(t - t_0)]$$

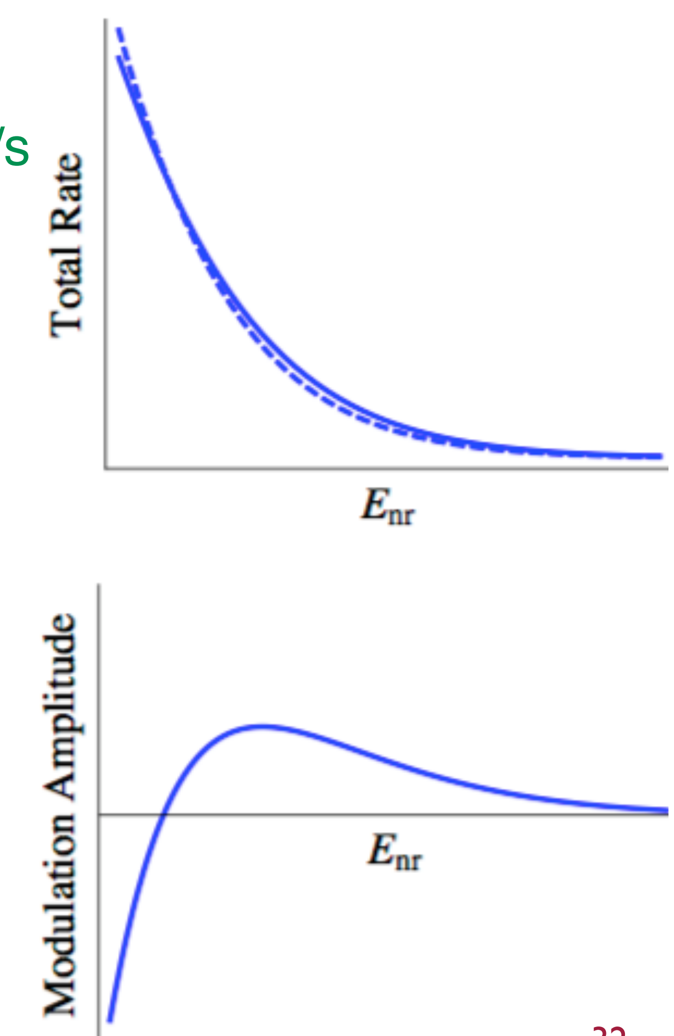


Distinctive modulation signal features:

T = 1 year t_0 = 2nd June

Pro: model independent

Con: requires detector stability and bkg control.



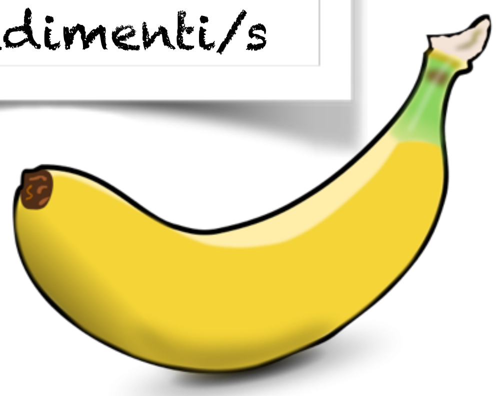
$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E) \cos\omega(t - t_0)$$

S_m/S_0 (modulation fraction) - for most models is O(1 - 10%)

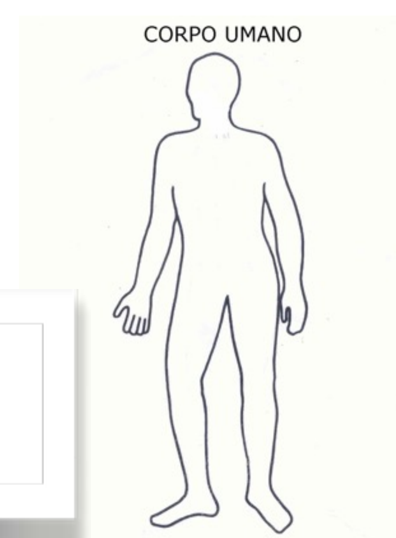
Natural Backgrounds

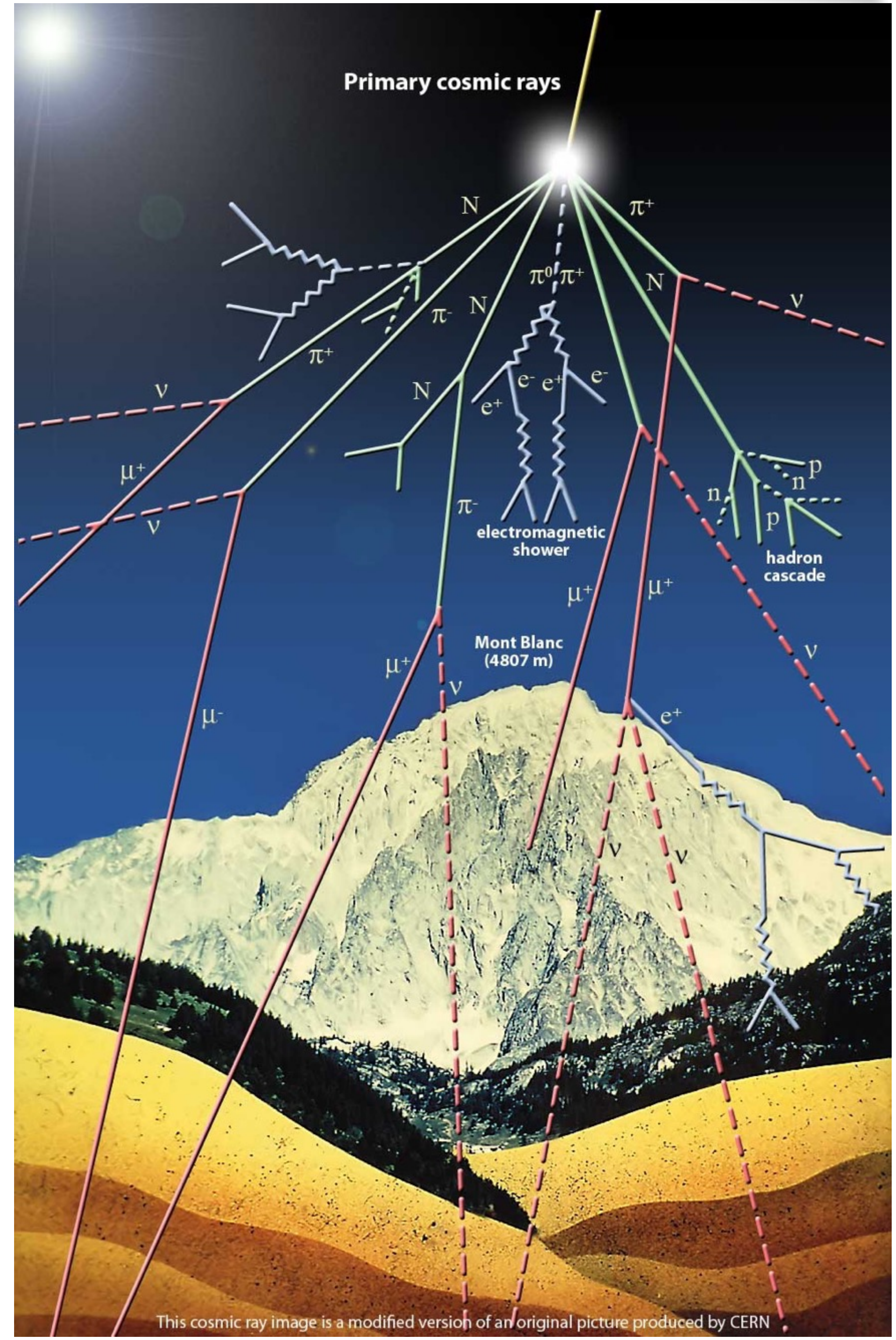
- Rare process subject to two major background
- Cosmic rays producing showers in the atmosphere
- Natural radioactivity!

15 decadimenti/s

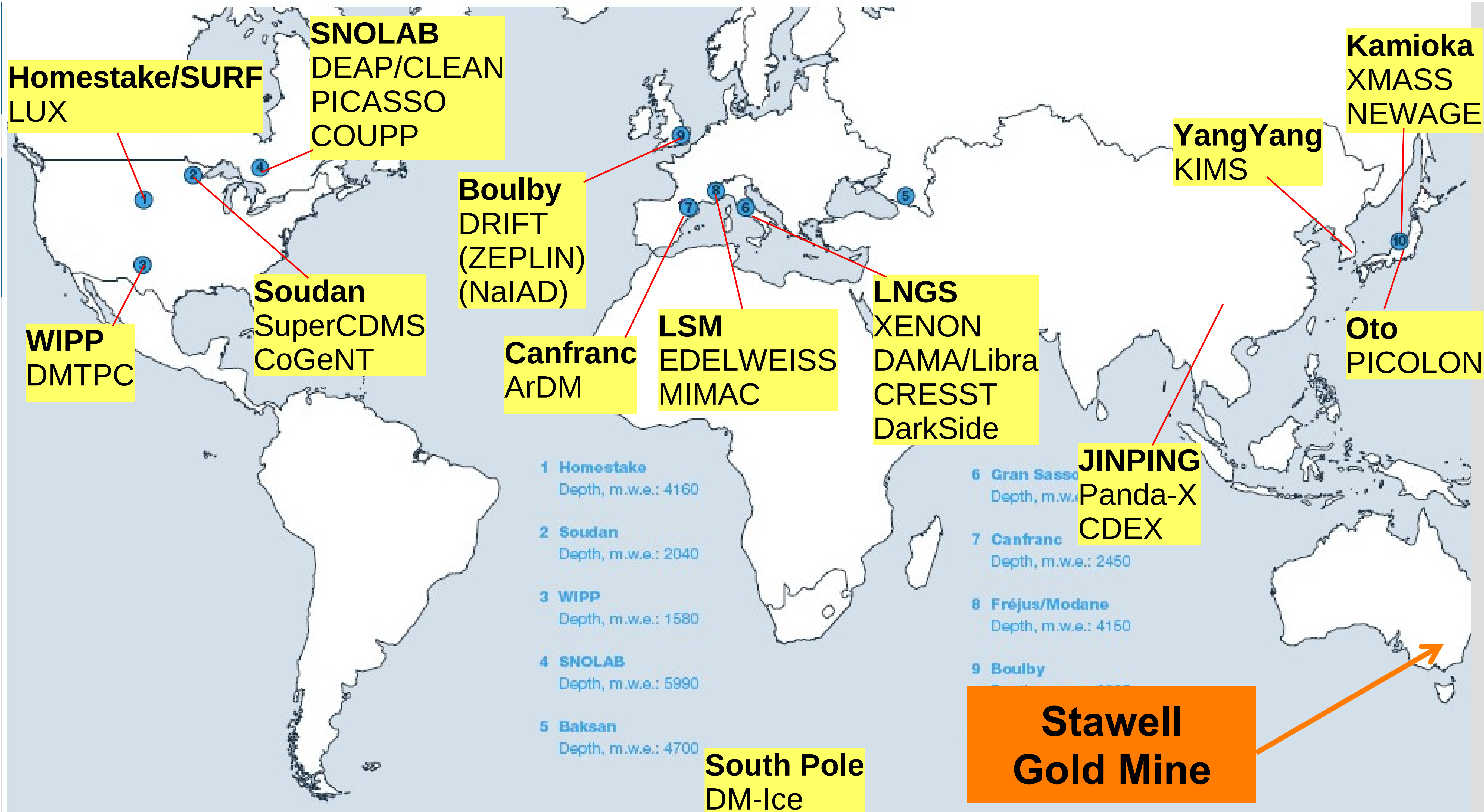


1 decadimento/s per grammo

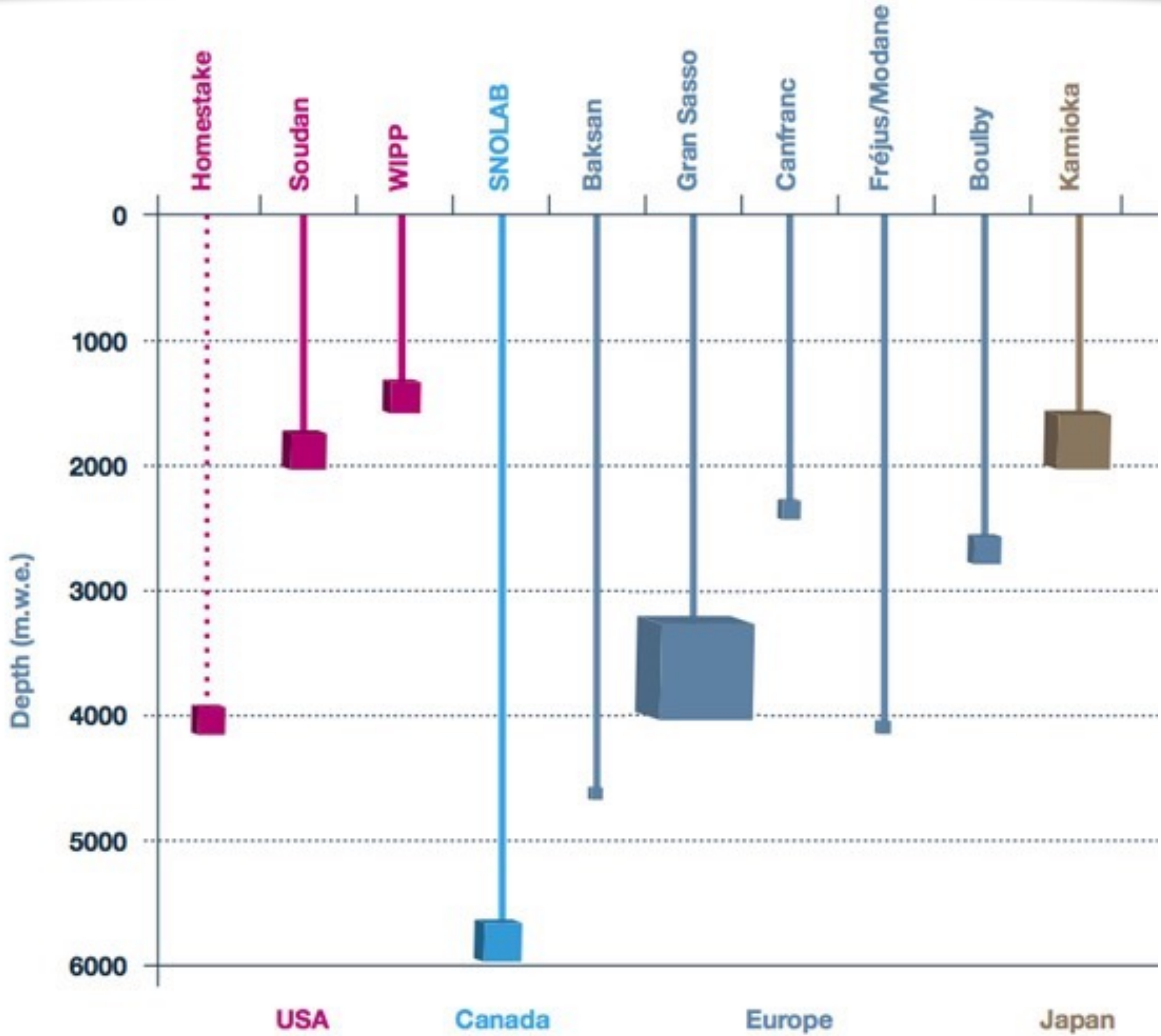




UNDERGROUND LABORATORIES



Underground Labs Worldwide



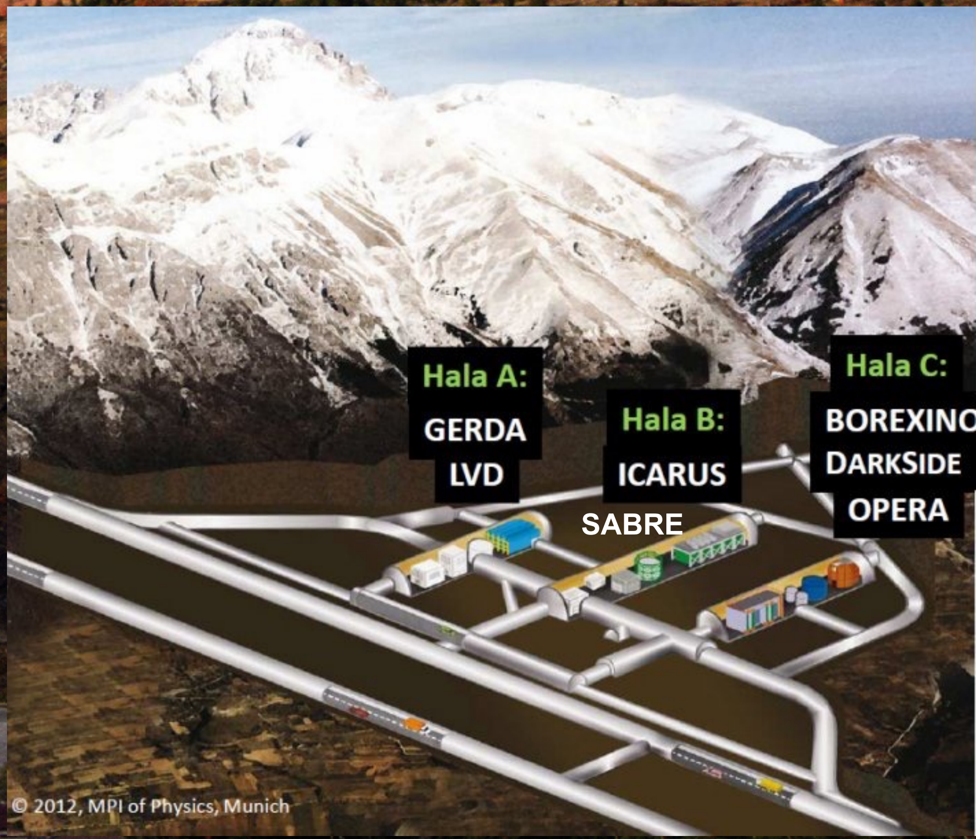
Laboratori Nazionali del Gran Sasso

1400 m di roccia sovrastante

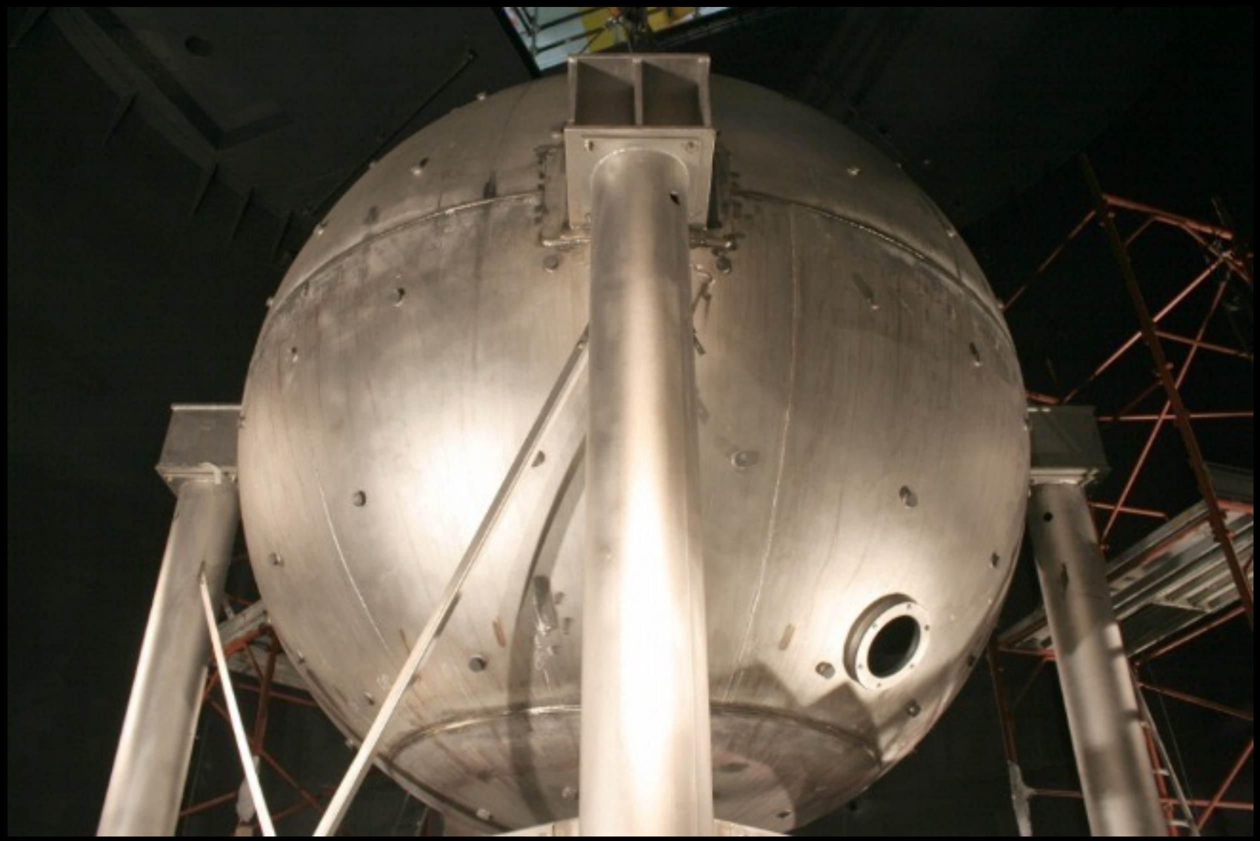
Superficie: 17 800 m^2

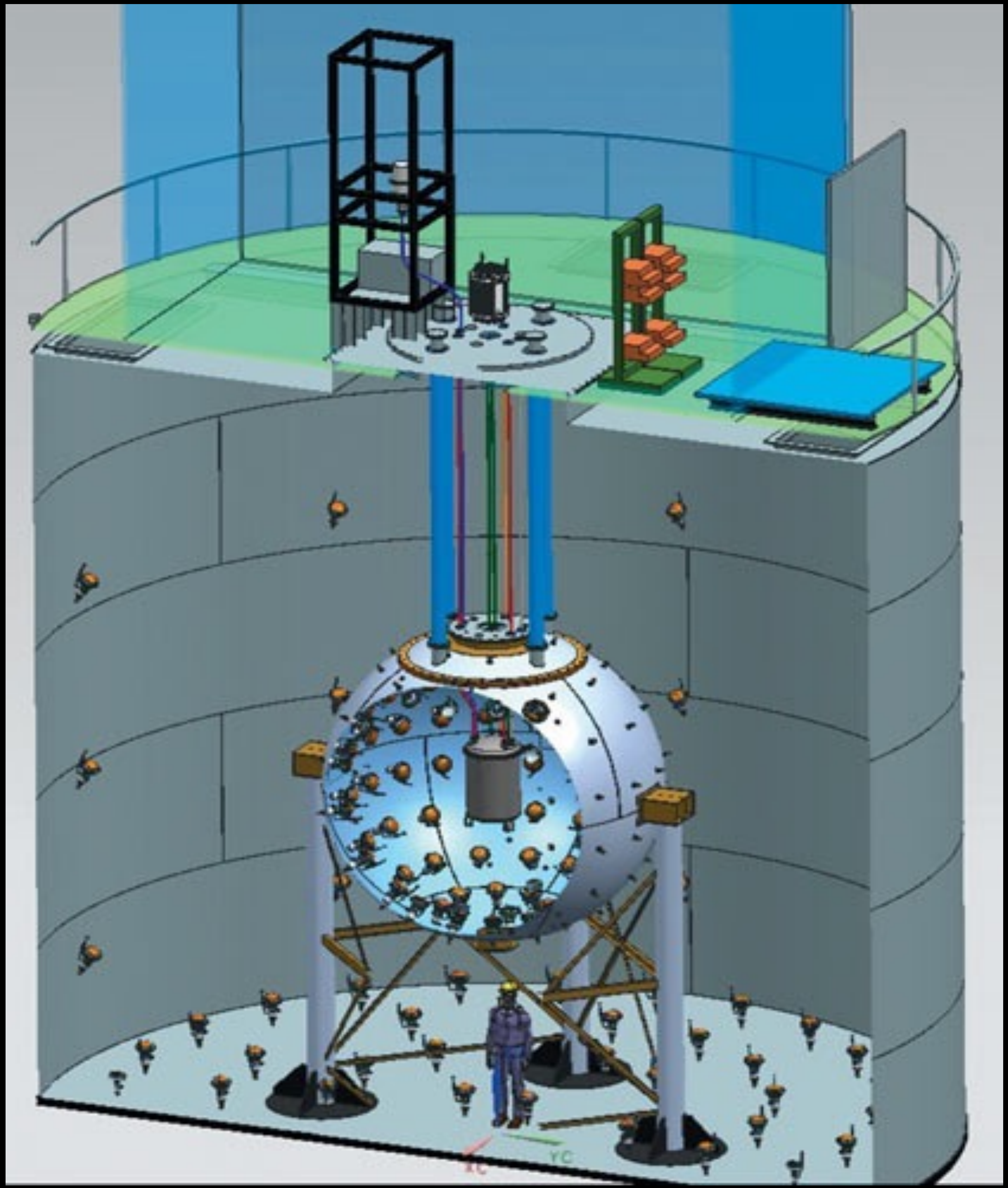
Volume: 180 000 m^3

Riduzione di un milione di volte del flusso di muoni



DARKSIDE





- Liquid (and gas) Argon used as target

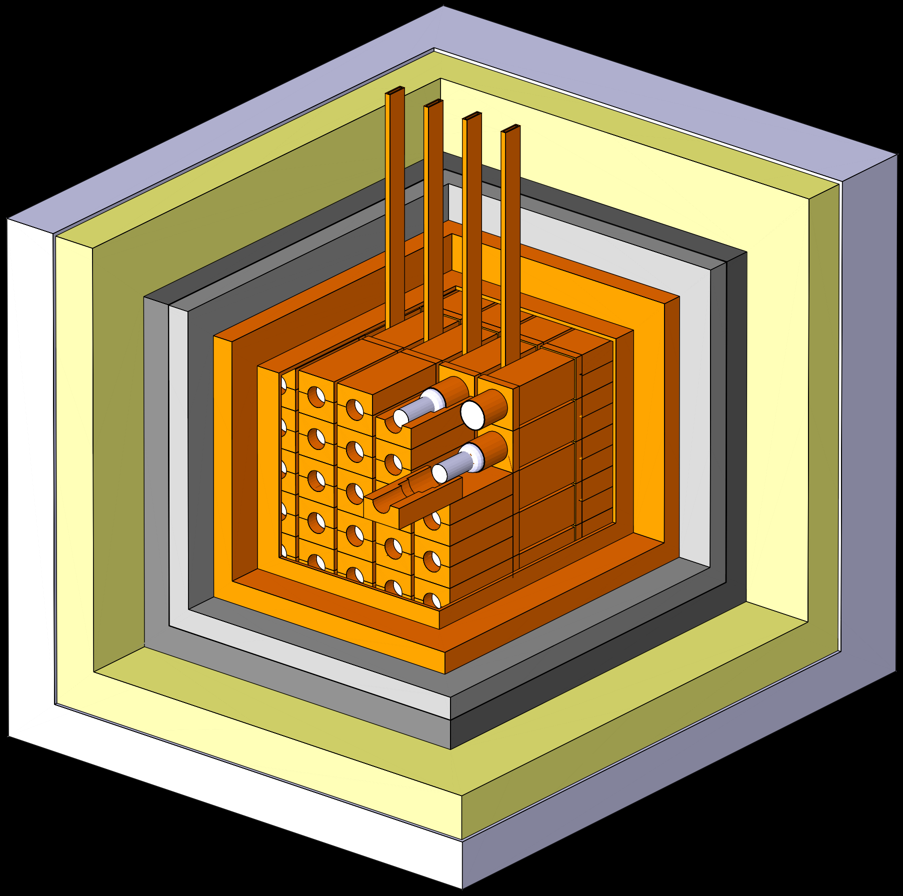
- No excess of signal events so far

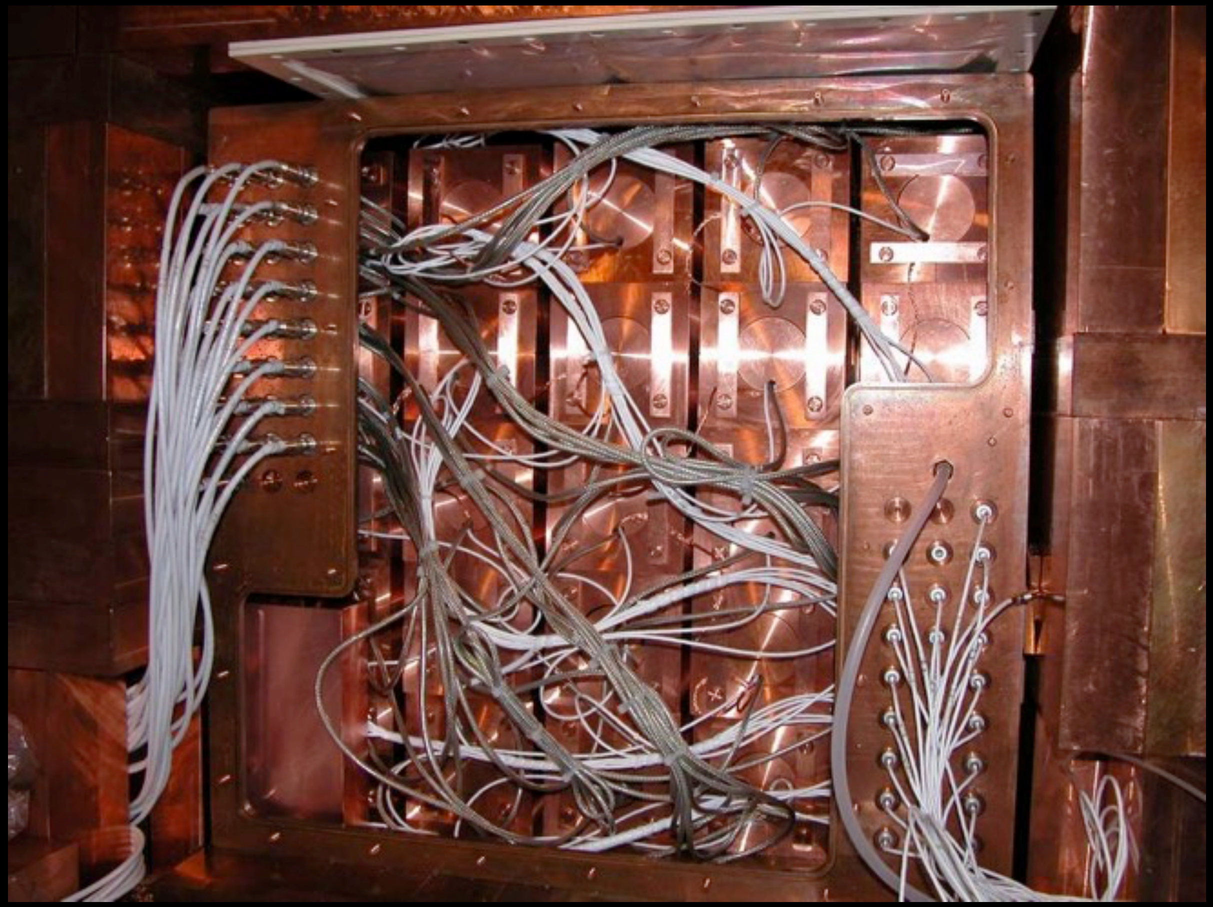
THE DAMA/LIBRA EXPERIMENT

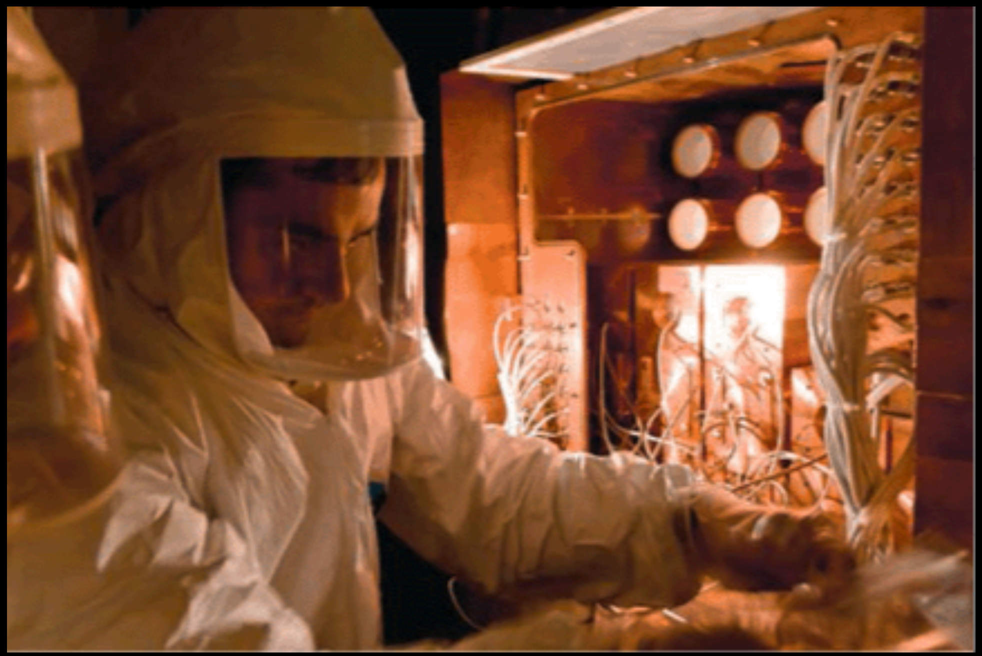
High Purity NaI (Tl) crystals

Located at LNGS:

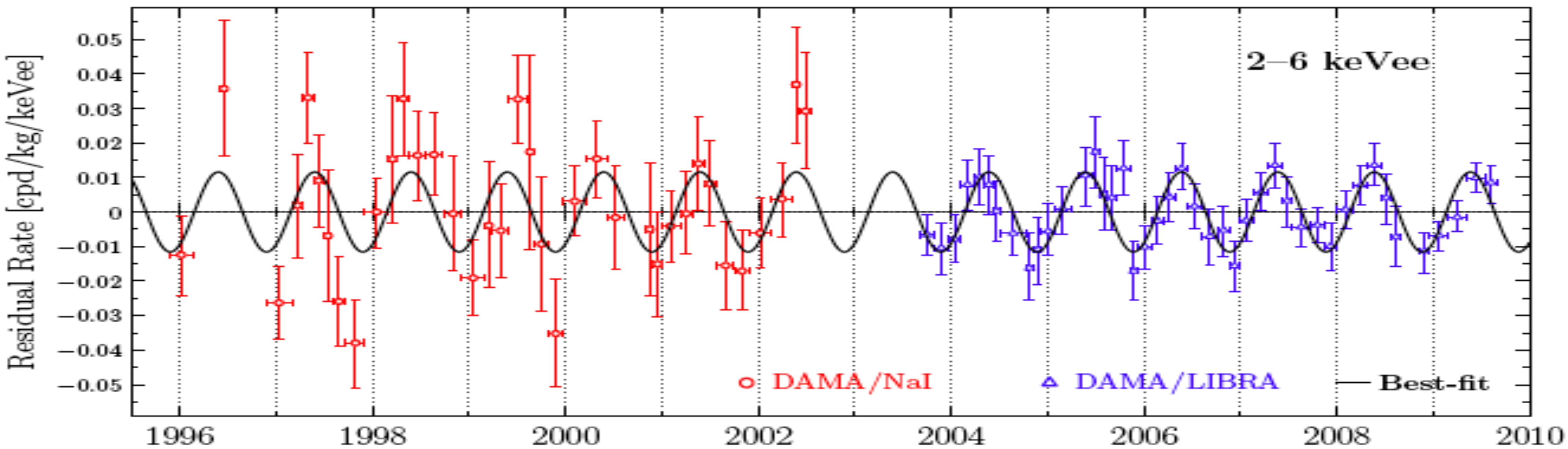
1. DAMA (100kg) 1996-2002
2. DAMA/LIBRA (250kg) Phase I: 2003-2010
3. DAMA/LIBRA (250kg) Phase II: 2011-…







DAMA/LIBRA RESULT

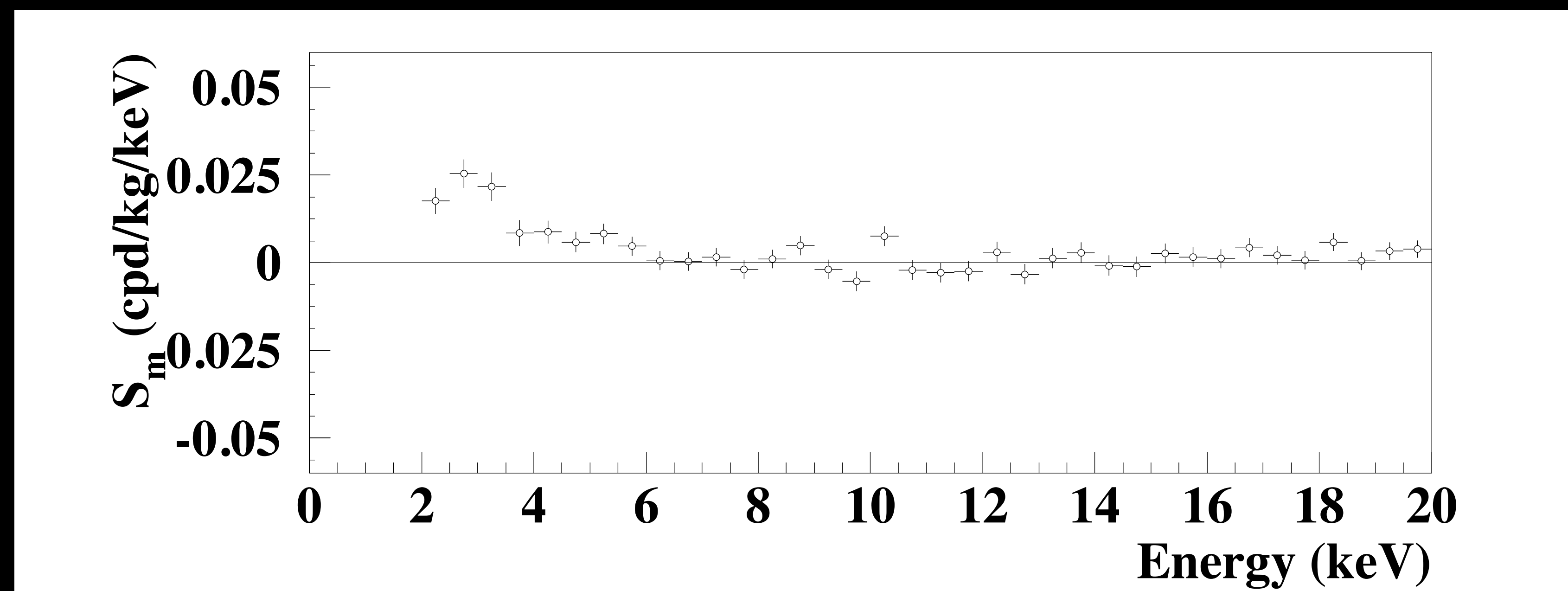


- 13 annual cycles (Dama/NaI + Dama/Libra)
  - $\chi 2/ndf = 70.4/86$
  - 9.3σ significance
- (0.998±0.002) year period
- Phase is (144±7) days vs. Exp. DM phase 152.5 days
- Amplitude (0.0112±0.0012) cdp/kg/keV (~ 1.2% of signal)
- Possible explanation: WIMP-nucleus SI interaction
  - $M_X \sim 10$ GeV/c^2 and $\sigma_X \sim 10^{-42}$ cm^2
  - *Very interesting signal but no confirmation from other experiments yet!*

THE DAMA/LIBRA MODULATION

Sources of modulations other than Dark Matter have been investigated and excluded:

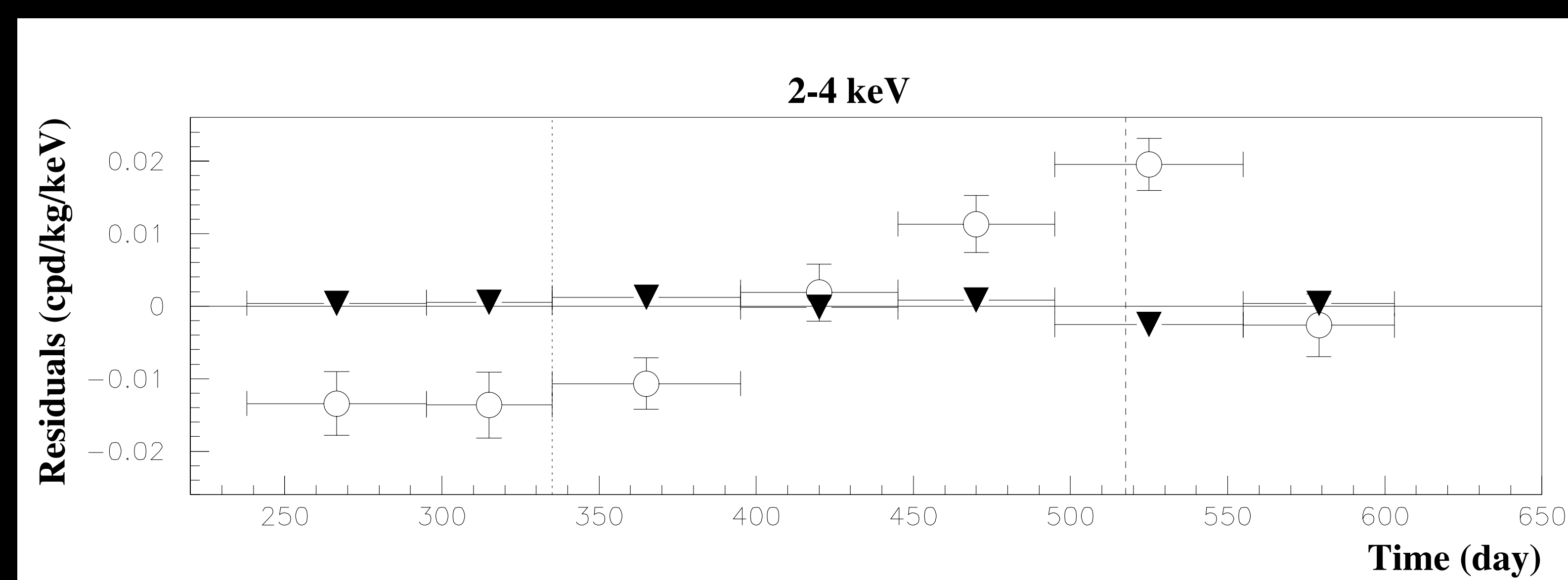
- ✓ radon
- ✓ temperature
- ✓ gas pressure
- ✓ electronic noise
- ✓ energy scale
- ✓ efficiencies
- ✓ environmental neutrons



No explanation of the modulation due to effects from known particles (neutrons, muons, neutrinos)

No modulation > 6keV

No modulation in multi-hit events

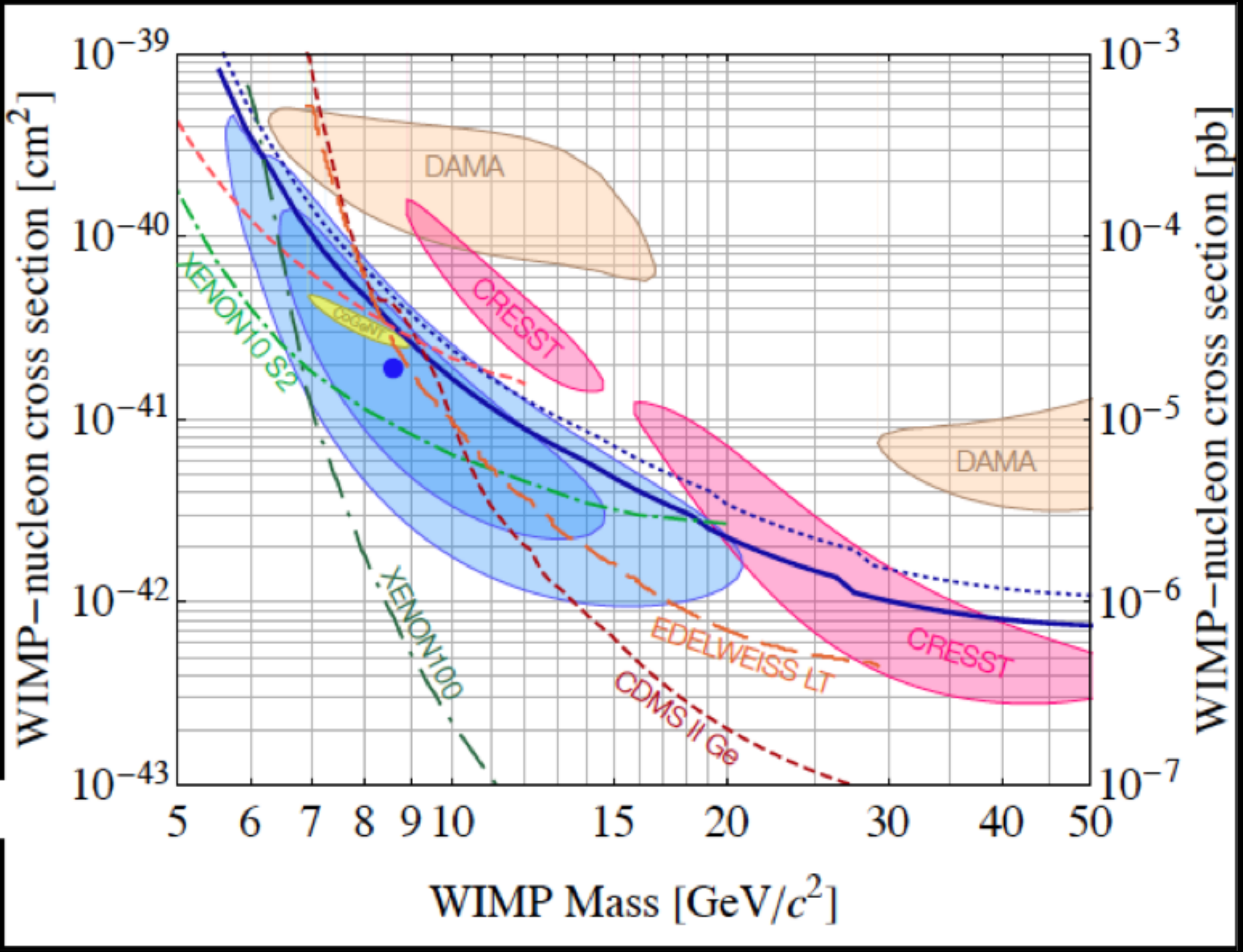


THE LOW-MASS POSITIVE RESULTS

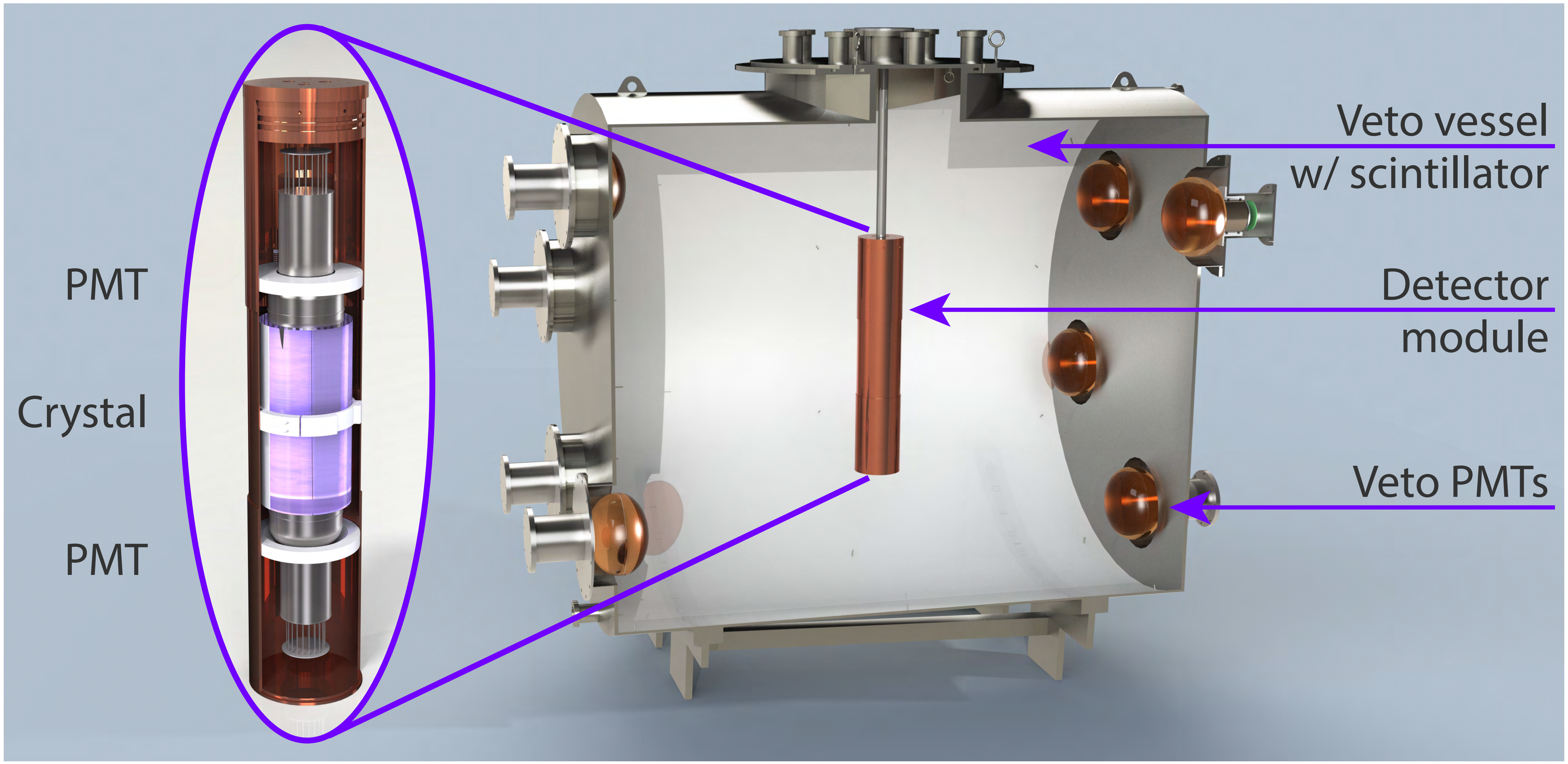
When interpreted in the WIMP framework (model dependent), tension with other results from experiments using different targets (XENON, LUX, CDMS, etc…)

The WIMP interpretation of the CRESST excess observed in the previous phase 1 is to a large extent ruled-out by new results.

No other NaI experiment so far has studied annual modulation effect with similar sensitivity
Confirmation of DAMA/LIBRA results still missing

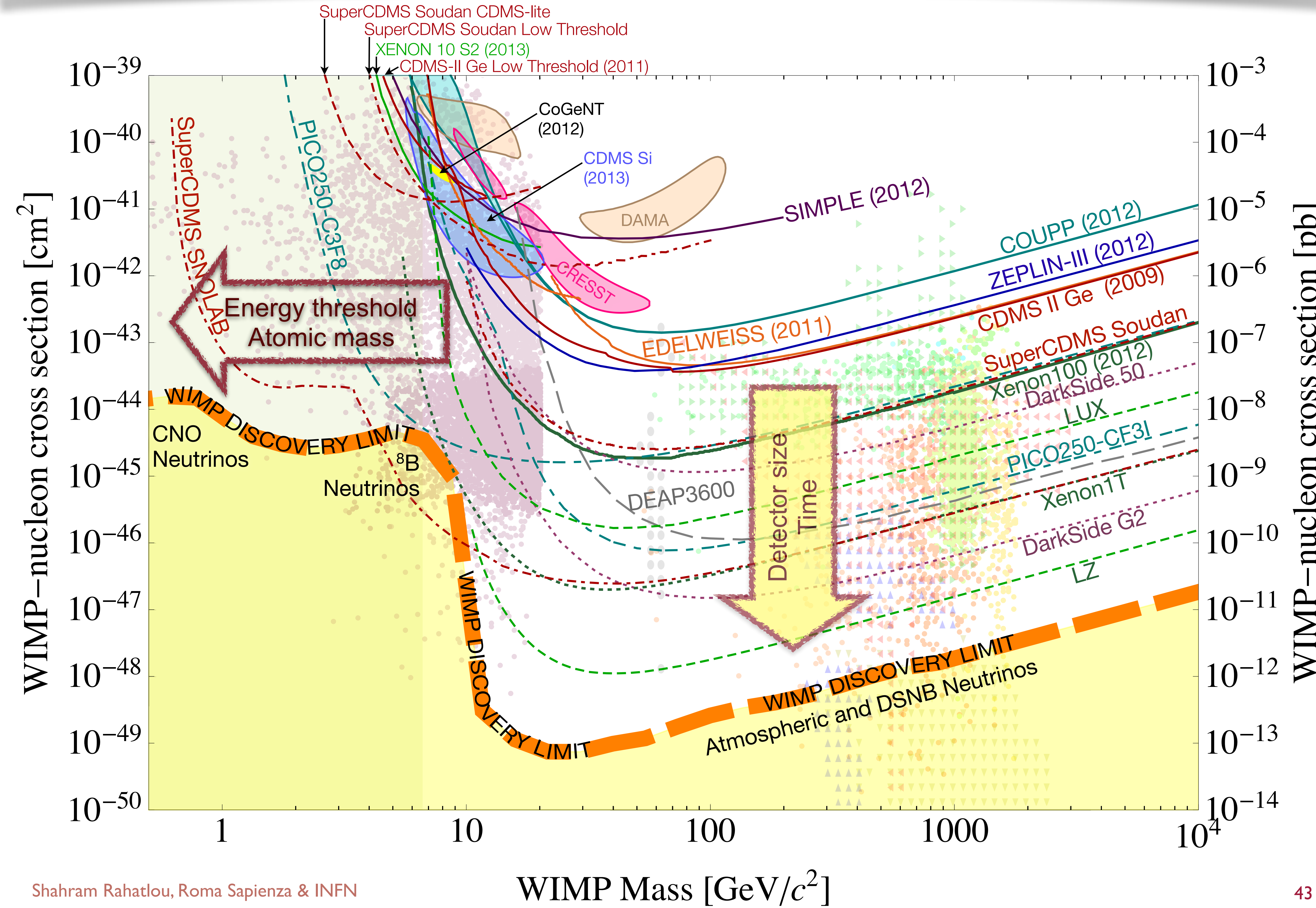


FUTURE EXPERIMENT: SABRE



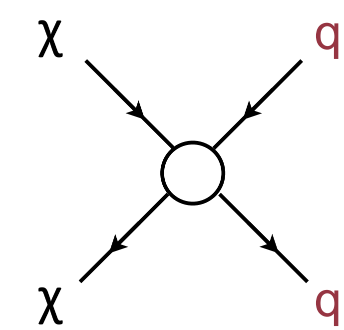
- At least 10 crystals of 5 kg each
  - aim at same radiopurity of DAMA or better
- Active shielding with liquid scintillator
- Prototype with one crystal to be tested in 2016-2017

CURRENT STATUS

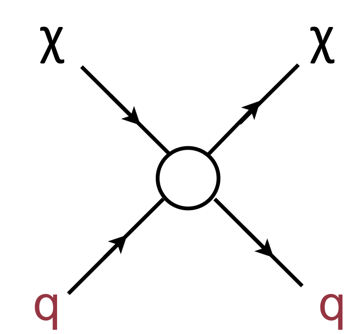


Dark Matter detection

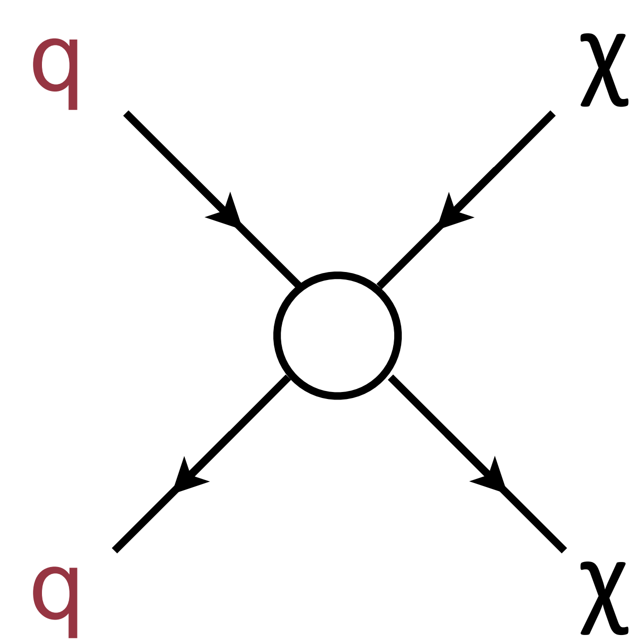
- Indirect detection
  - search for production of DM annihilation
  - high energy photons, particle-anti-particle pairs
  - search for ultra-relativistic objects produced in galactic halo
  - observatory on earth-bound or with satellites



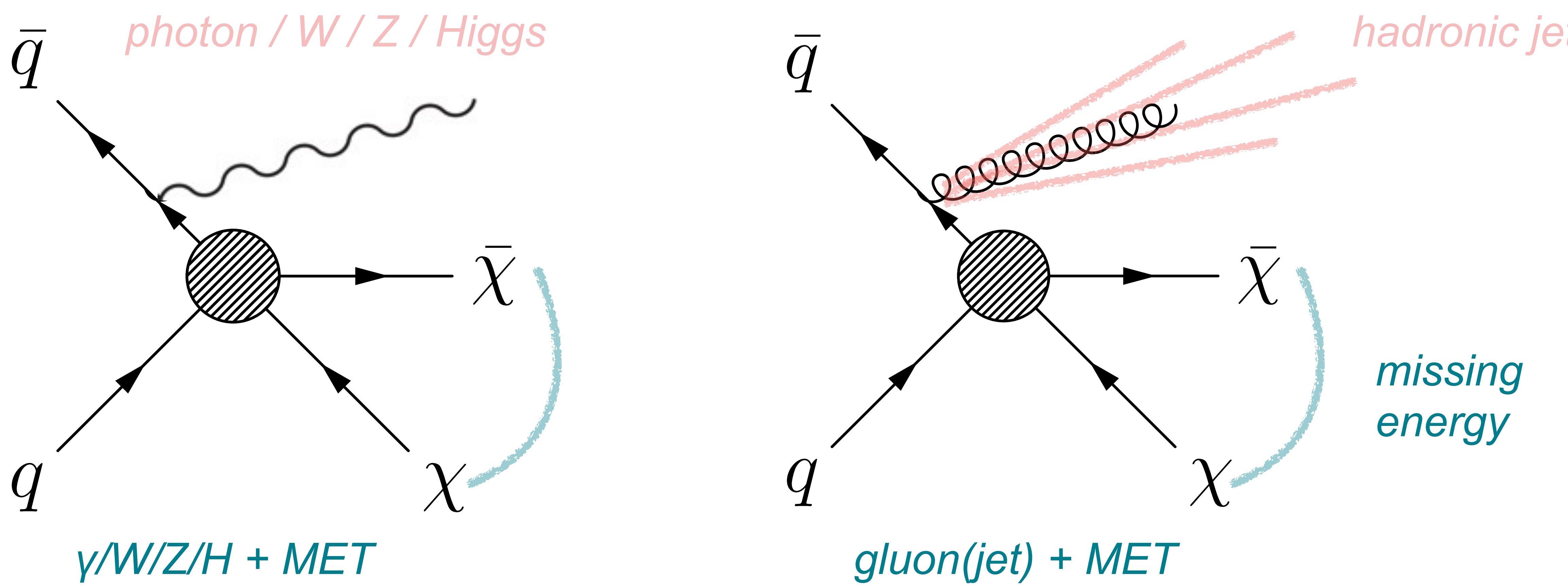
- Direct detection
  - Observe recoil of dark matter from nucleus



- Pair production at LHC
  - large missing energy in the detector
  - need to identify ("tag") events of interest

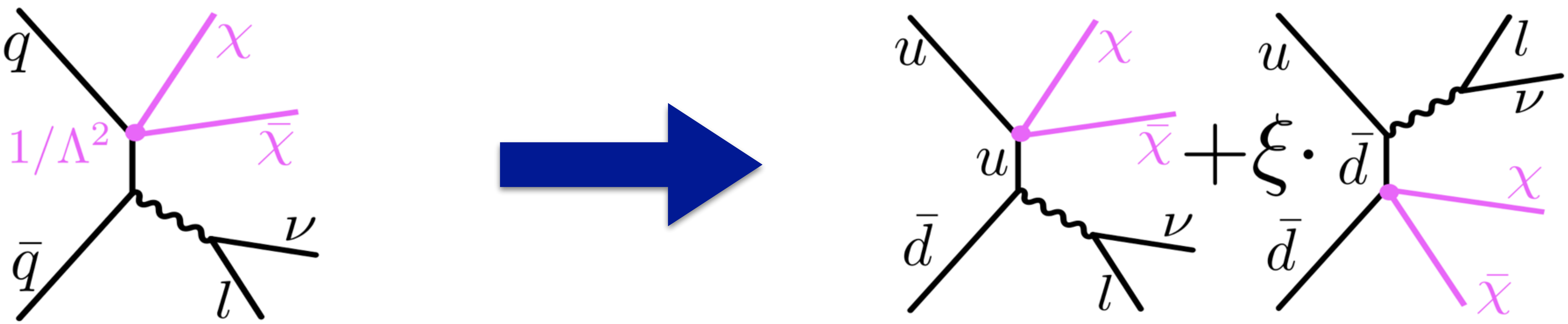


DARK MATTER PRODUCTION AT LHC



- EW bosons and gluons can be radiated by initial partons
- Presence of high energy photon/W/Z/Higgs or jet(s) *in addition* to large missing transverse energy
- Gluon radiation at higher rate than EW bosons
  – strong interaction vs. electromagnetic

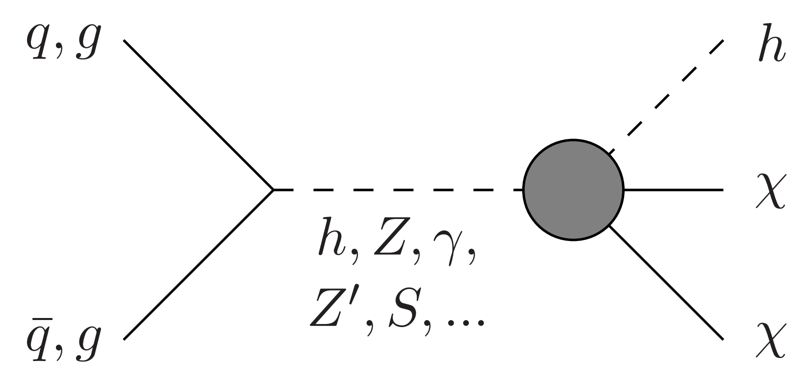
W + MET



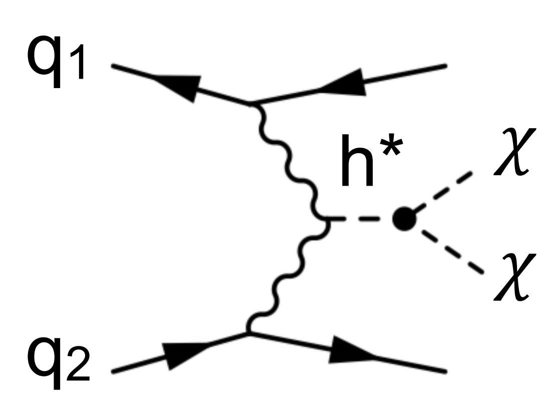
- W being charged can distinguish between u and d quarks
- Need to account for interference

HIGGS PORTAL TO DARK MATTER

- Discovery of Higgs has opened new doors to Dark matter
- New searches proposed to investigate coupling of dark matter candidates to Higgs boson
- mono-Higgs: Higgs + missing energy through new operator
  - produced via both quarks and gluons

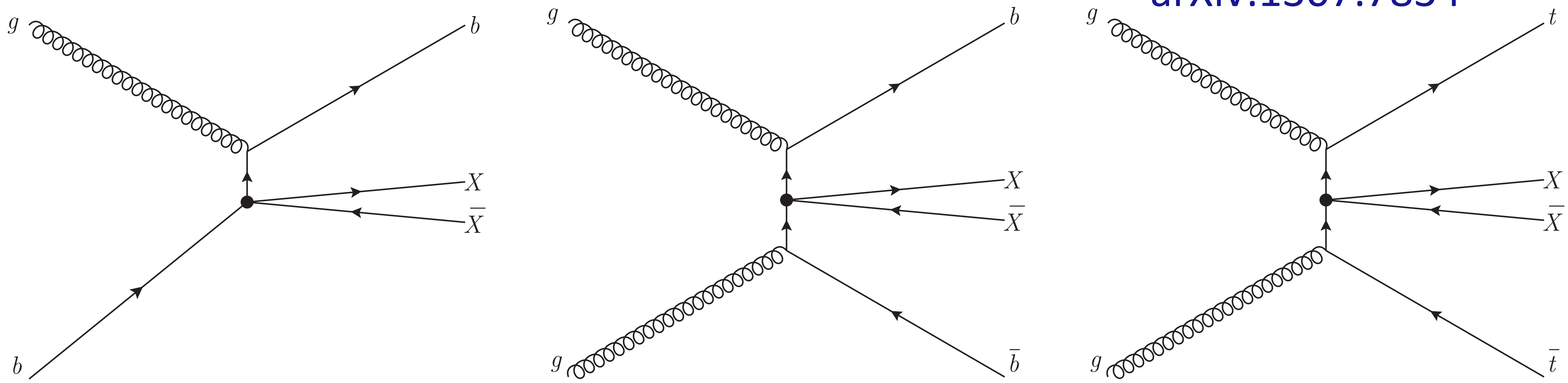


- Higgs mediation: dark matter candidate couples only to Higgs and no other SM particle
  - $m_{DM} < m_H/2$: Higgs decay to DM pair
    - Currently branching ratio of invisible Higgs decays < ~60%
      - ➡ expect to reach BR < 0.2-0.3 with 3000 fb^{-1}
  - $m_{DM} > m_H/2$: DM pair from virtual Higgs
    - Distinctive signature with forward jets



THINKING OUT OF THE BOX: MONO-b/t

arXiv:1307.7834



- Important for a scalar mediator operator
  - Structure constrained by flavor violation
- Enhanced coupling for third generation quark
  - coupling proportional to mass
- Dedicated analysis exploiting boosted top and b-tag more competitive than generic mono-jet search
- Efforts underway in ATLAS
  - reinterpretation of existing SUSY results performed by theorists

SUMMARY OF CURRENT SEARCHES

- mono-jet
  - strongest constraints
- mono-photon
  - more challenging for background estimation
  - less powerful: EW vs. strong interaction
- mono-W/Z leptonic
  - clean signature and simple trigger
  - penalized by W/Z branching fraction
- mono-W/Z hadronic
  - larger statistics with larger background

Modeling the DM Interaction

- Pair-production of χ can be characterized by a contact interaction with operators

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

vector --> spin independent (SI)

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

axial-vector --> spin-dependent (SD)

- Cross section depends on the mass (m_χ) and the scale Λ (for couplings g_χ, g_q)

spin-independent and spin-dependent cross sections

$$\sigma_{SI} = 9\frac{\mu^2}{\pi\Lambda^4} \qquad \Lambda = M/\sqrt{g_\chi g_q}$$

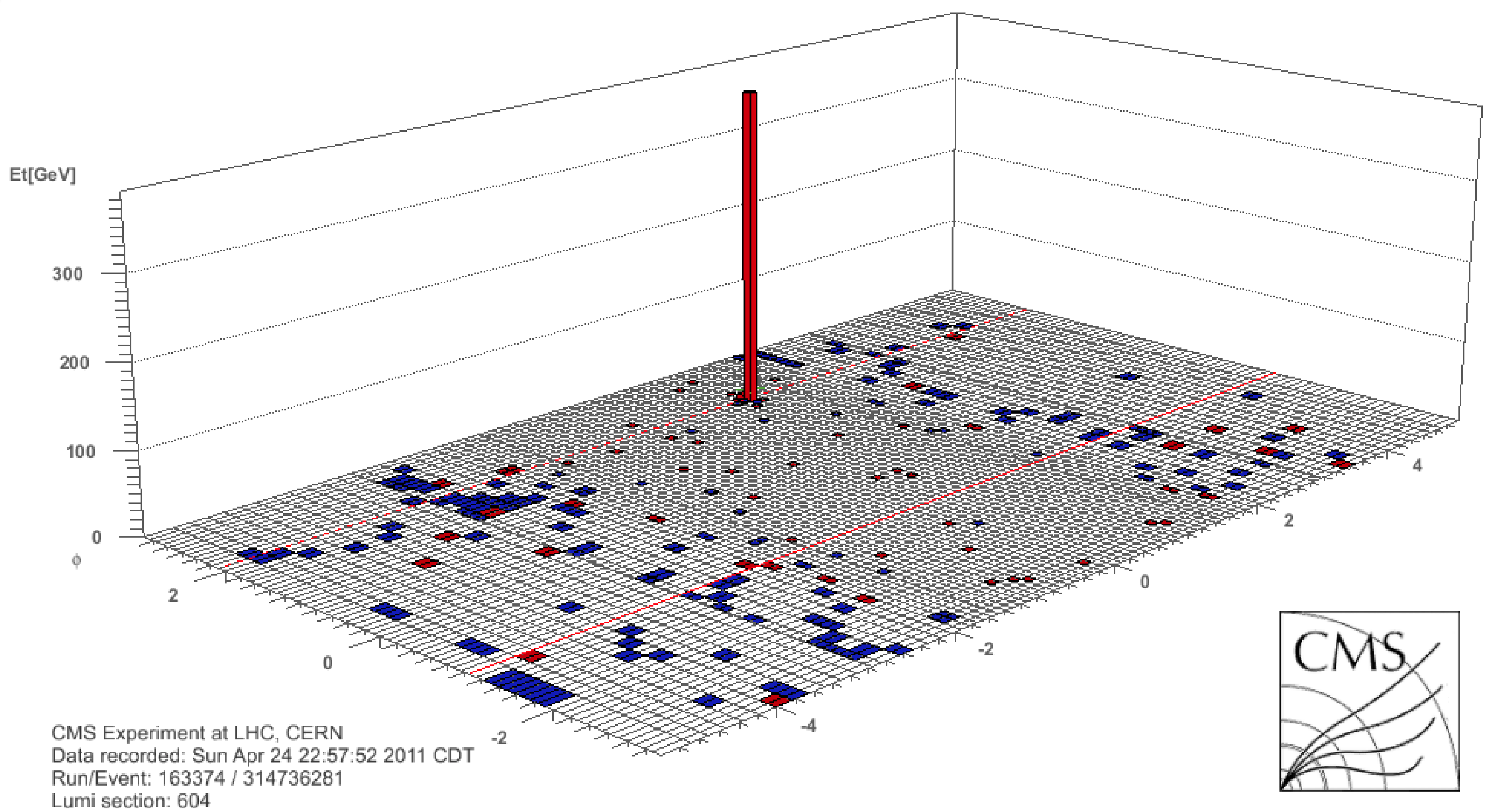
$$\sigma_{SD} = 0.33\frac{\mu^2}{\pi\Lambda^4} \qquad \mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

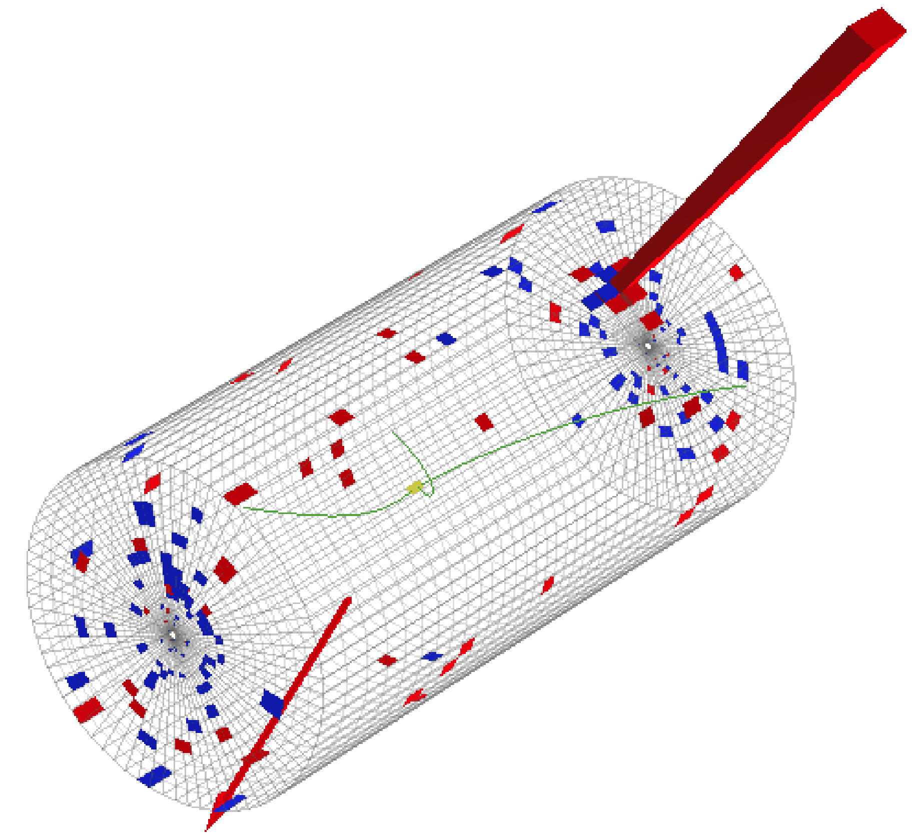
[Bai, Fox and Harnik, JHEP 1012:048 (2010)]

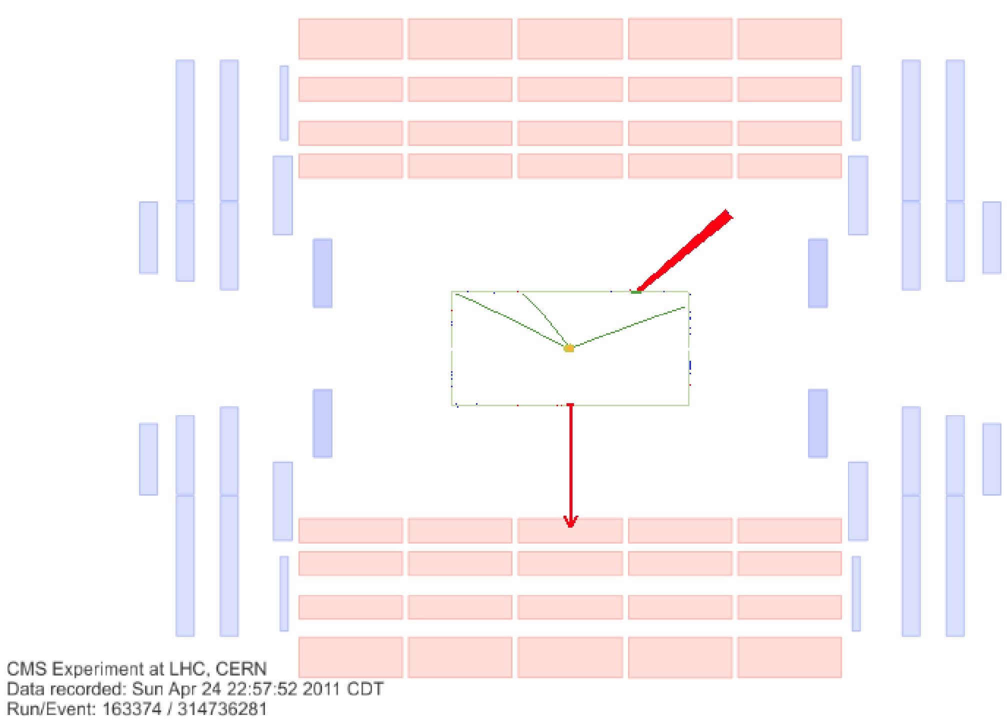
[Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, Phys.Rev.D82:116010 (2010)]

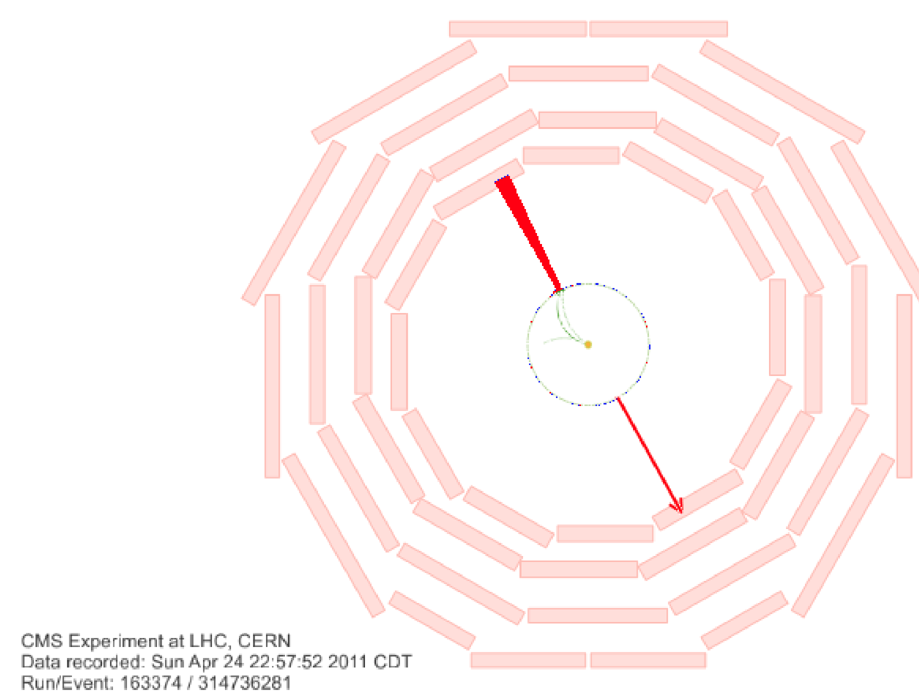
[Beltran, Hooper, Kolb, Krusberg, Tait, JHEP 1009:037 (2010)]

Monophoton Event



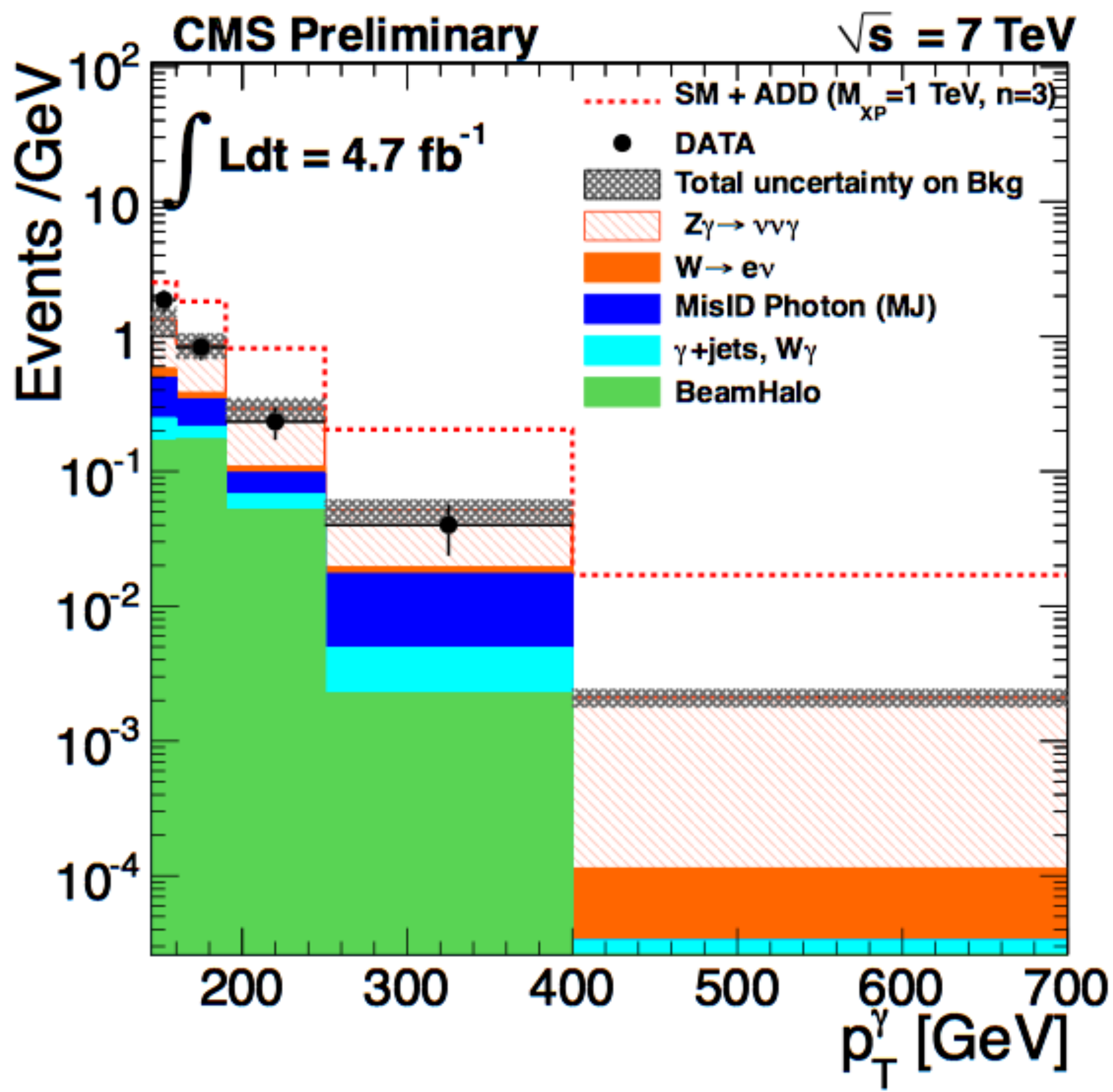






Monophoton – Selection

- Require one photon in events with
  - High energy photon: $p_T(\gamma) > 145$ GeV/c
  - central part of calorimeter: $|\eta| < 1.442$
  - Shower shape consistent with photon
  - MET > 130 GeV



Monophoton Backgrounds

- Backgrounds from pp collisions

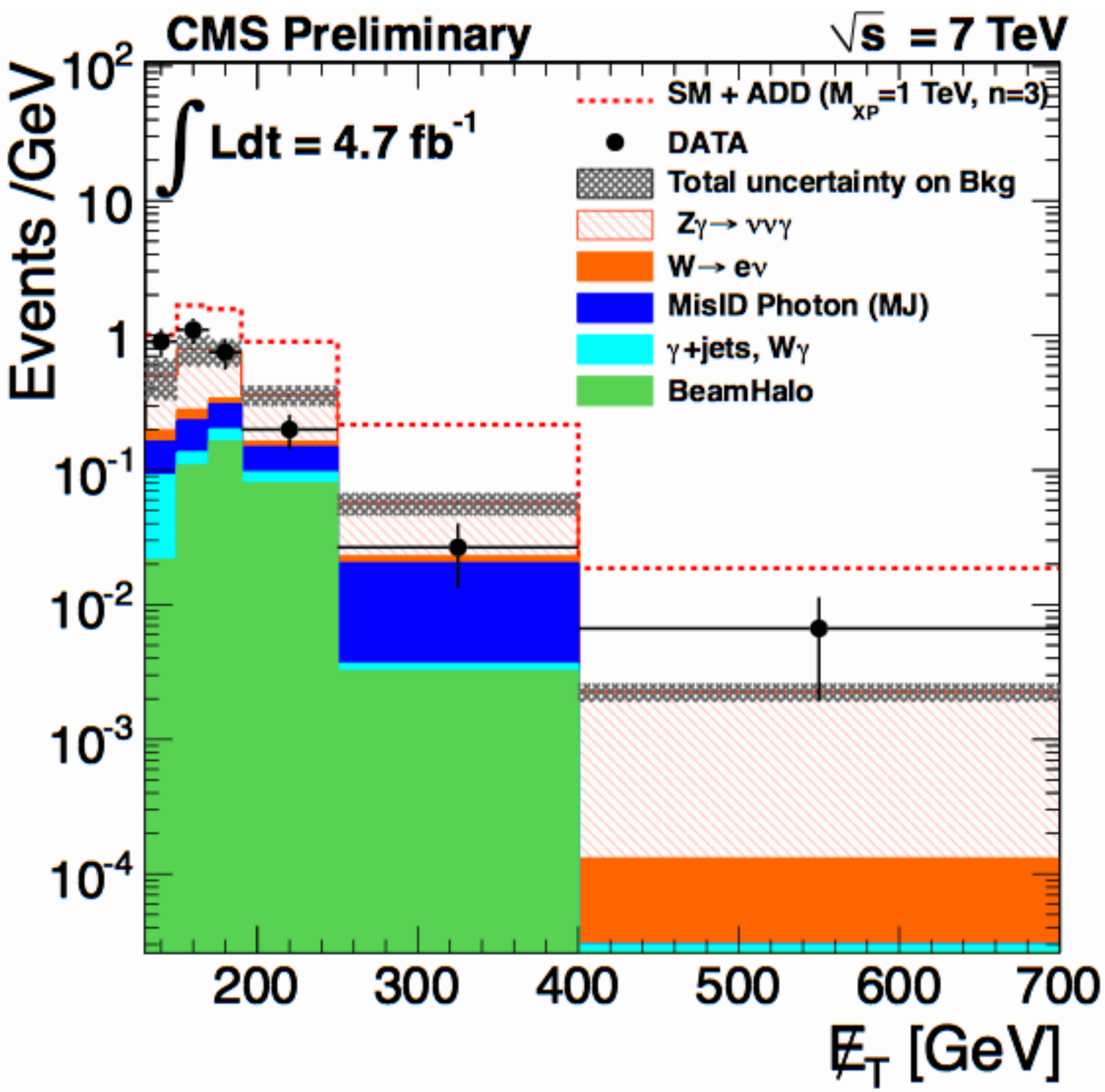
$pp \to Z\,\gamma \to \nu\nu\,\gamma$	irreducible background
$pp \to W \to e\nu$	electron mis-identified as photon
$pp \to jets \to$ "γ" + MET	one jet mimics photon, MET from jet mis-measurement
$pp \to \gamma + jet$	MET from jet mis-measurement
$pp \to W\,\gamma \to l\nu\,\gamma$	charged lepton escapes detection
$pp \to \gamma\,\gamma$	one photon mis-measured to give MET

- Backgrounds unrelated to pp collisions

Showers induced by cosmics	identified and removed
Neutron-induced signals	identified and removed
Beam halo	mostly removed; a residual contribution estimated

- Look for excess of events above background
  – counting experiment

Monophoton Search



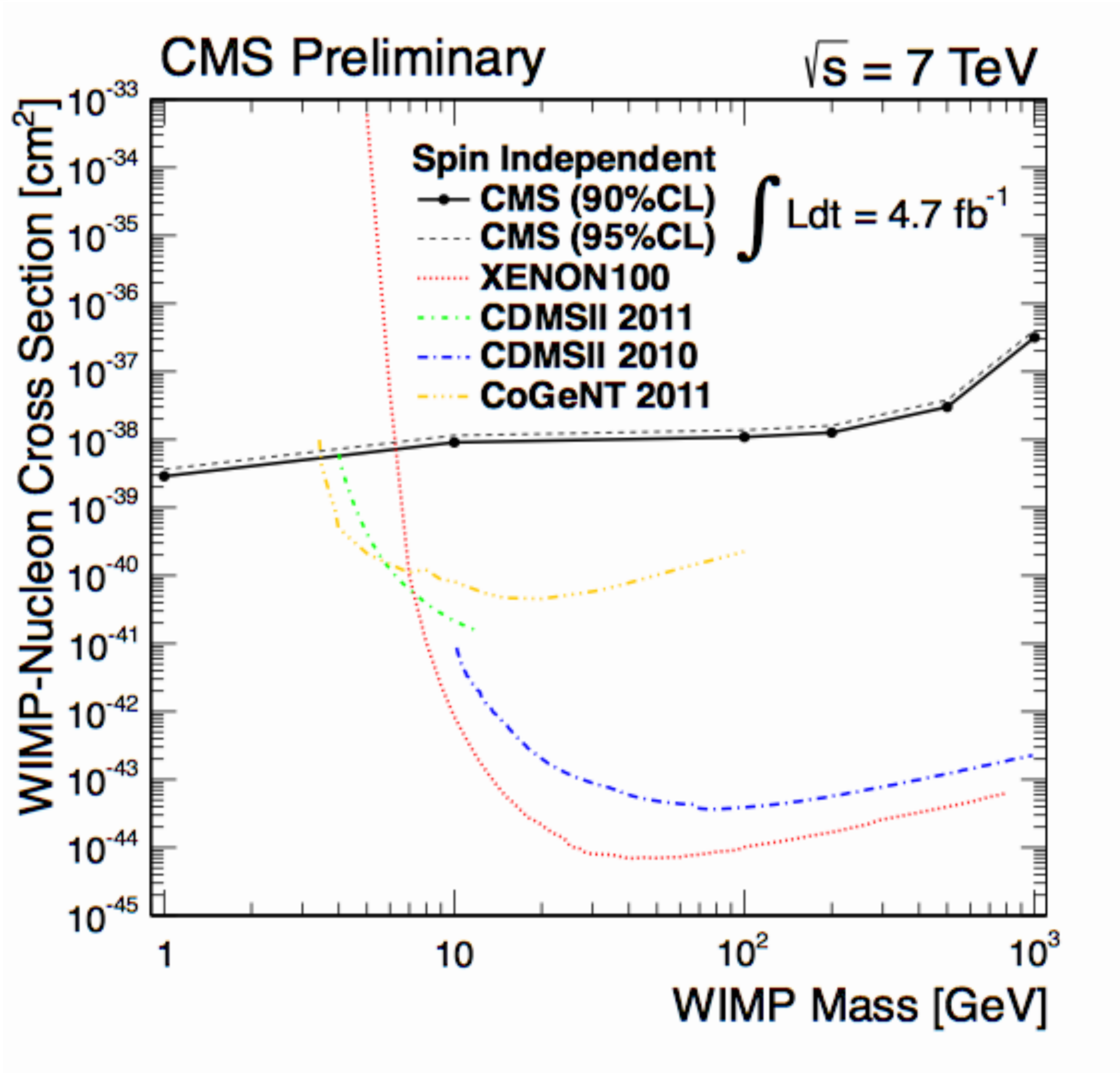
Source	Estimate
Jet Mimics Photon	11.2 ± 2.8
Beam Halo	11.1 ± 5.6
Electron Mimics Photon	3.5 ± 1.5
$W\gamma$	2.8 ± 0.9
γ+jet	0.5 ± 0.2
$\gamma\gamma$	0.5 ± 0.3
$Z(\nu\bar{\nu})\gamma$	42.4 ± 6.3
Total Background	71.9 ± 9.1
Total Observed Candidates	73

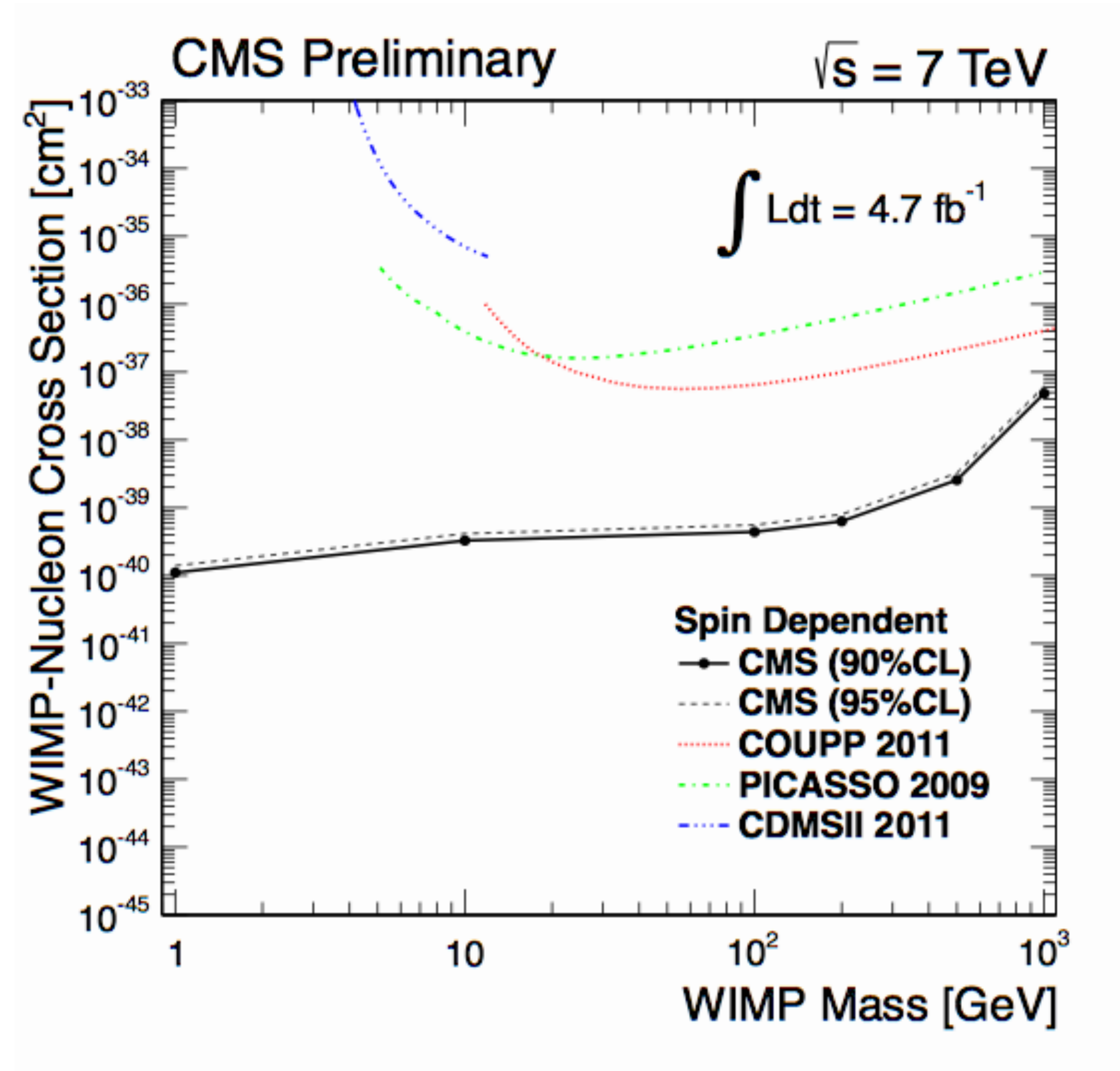
Systematic uncertainties

- Stats. uncertainty 1.7%
- Photon PT uncertainty 2.3%
- Jet Energy Scale 1.2%
- MET modelling 0.5%
- Pile-up modelling 2.4%

- observed events in agreement with expected background
  - compatible with no signal
- Provide upper limit on production cross section

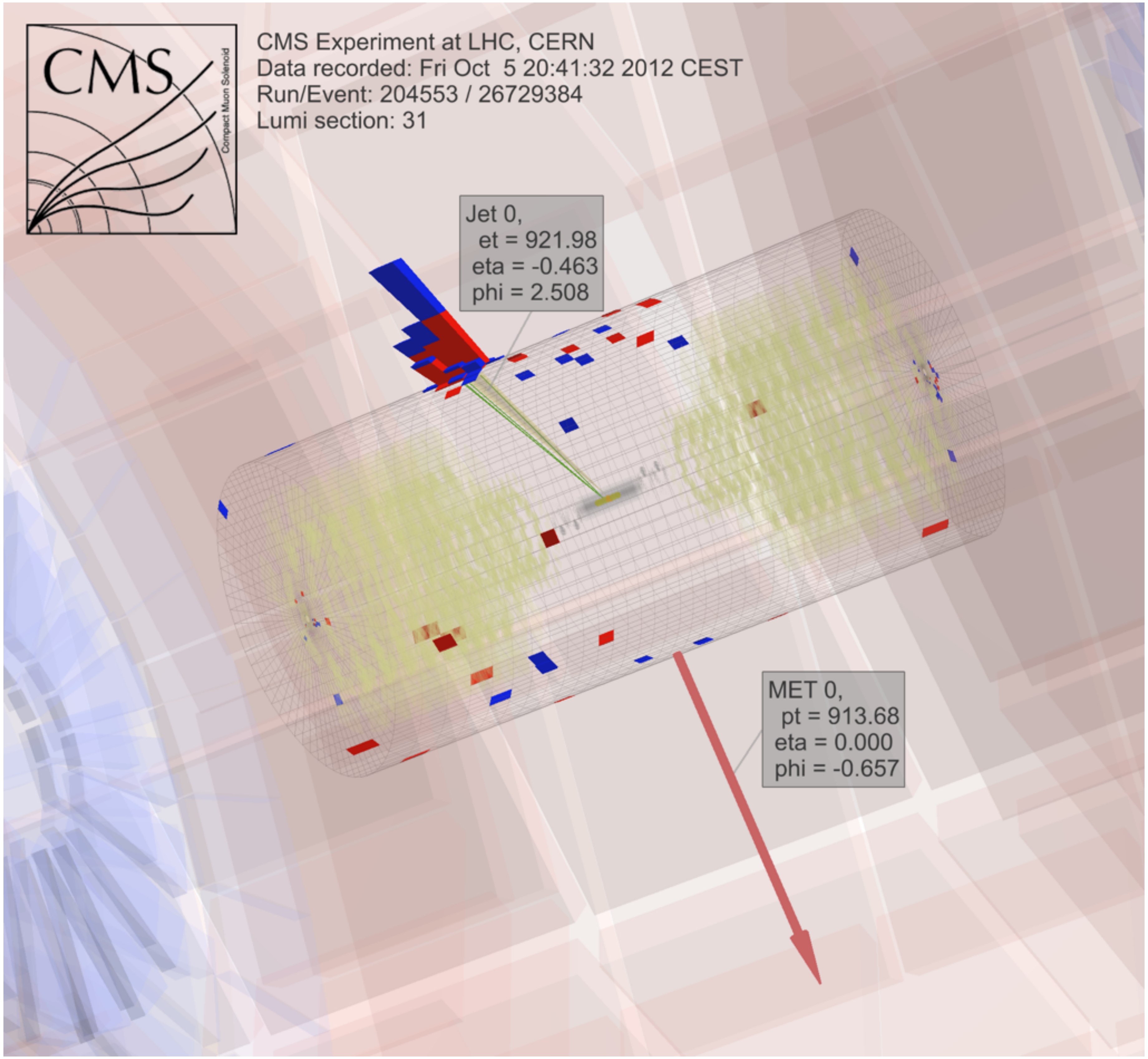
MONOPHOTON LIMITS ON CROSS SECTION



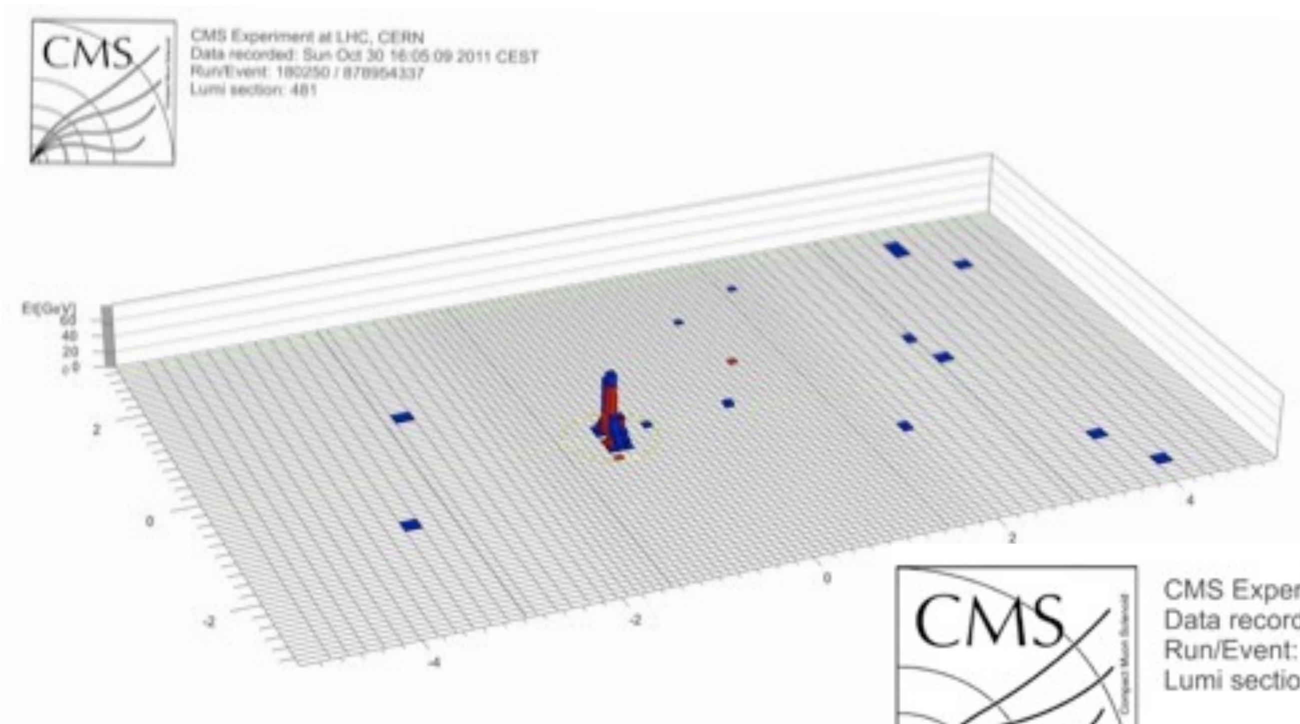


- Extraction of χ-nucleon cross section
- Upper limits on cross sections give lower limits on Λ, assuming a Λ^{-4} behaviour
- Lower limits on Λ are then used to plot χ-nucleon cross section limits versus DM mass

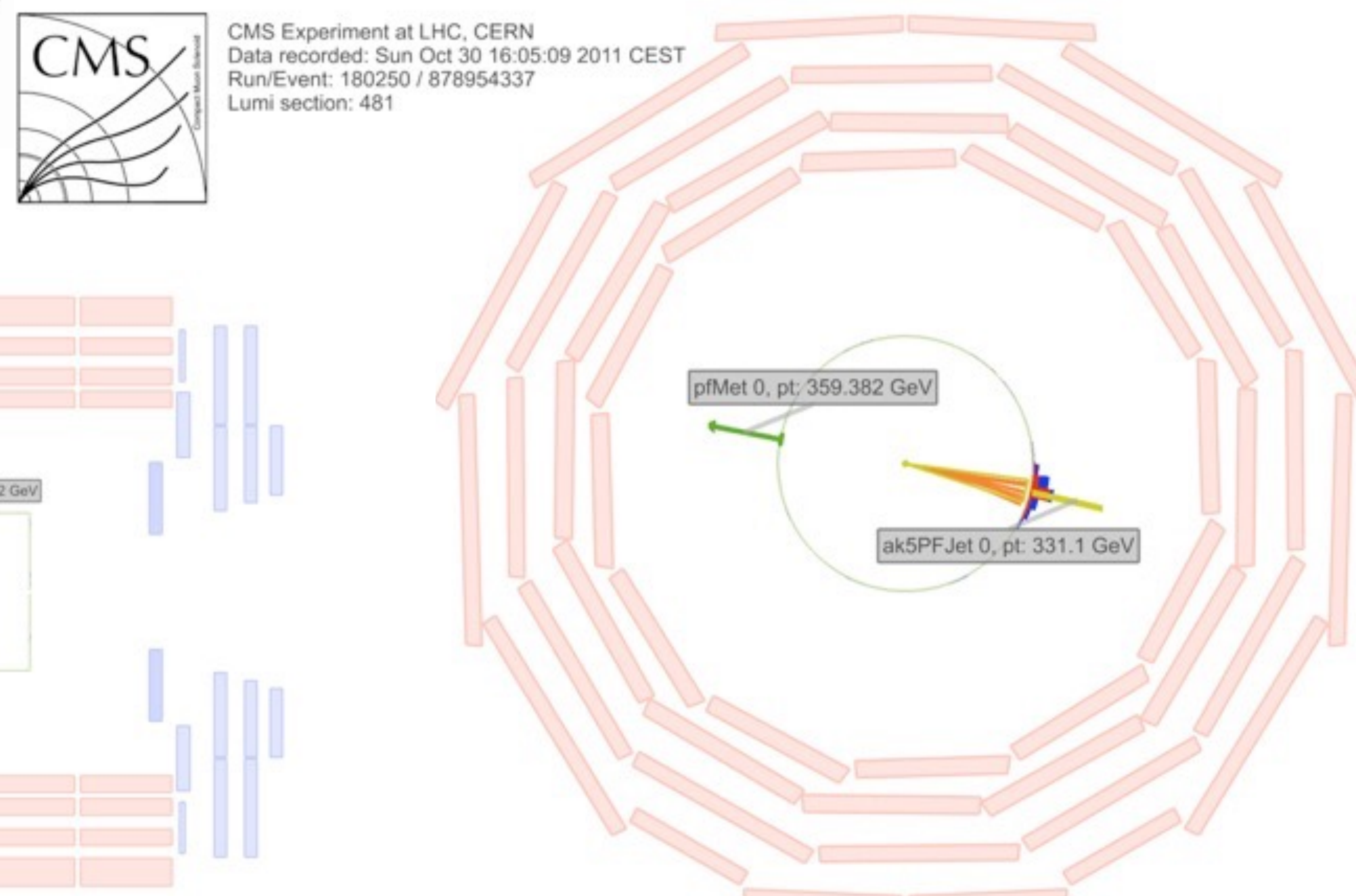
MONOJET EVENT

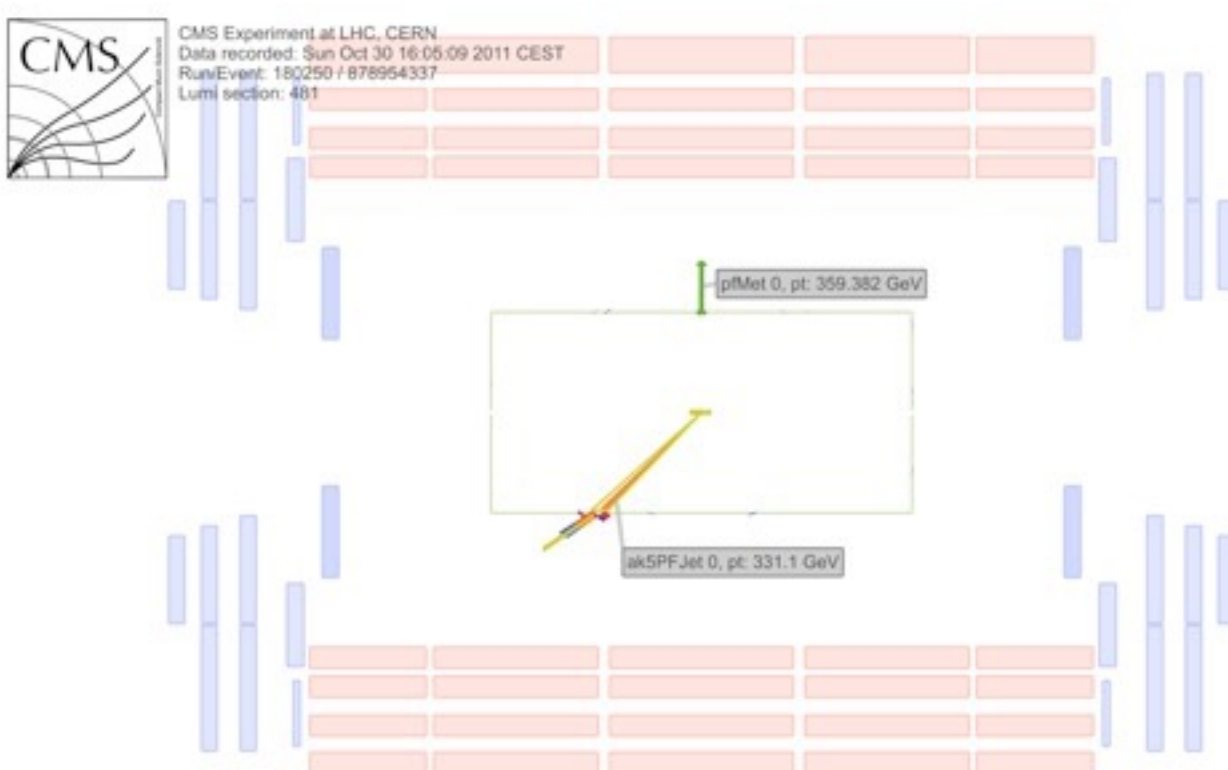


MONOJET EVENT



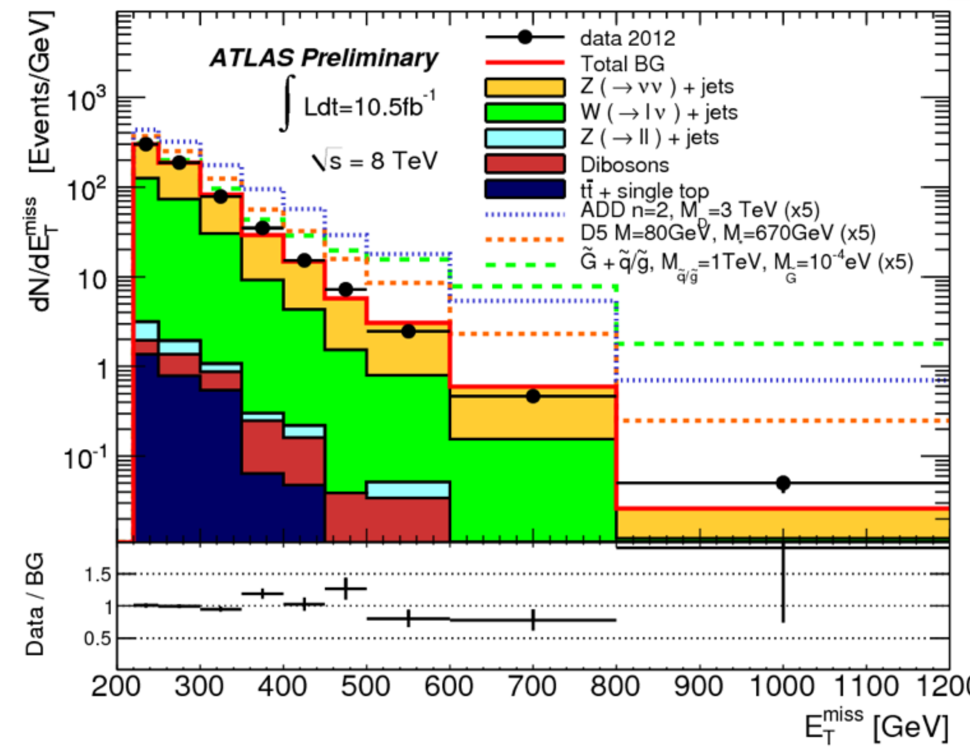
MET = 359 GeV
p_T(jet1) = 331 GeV

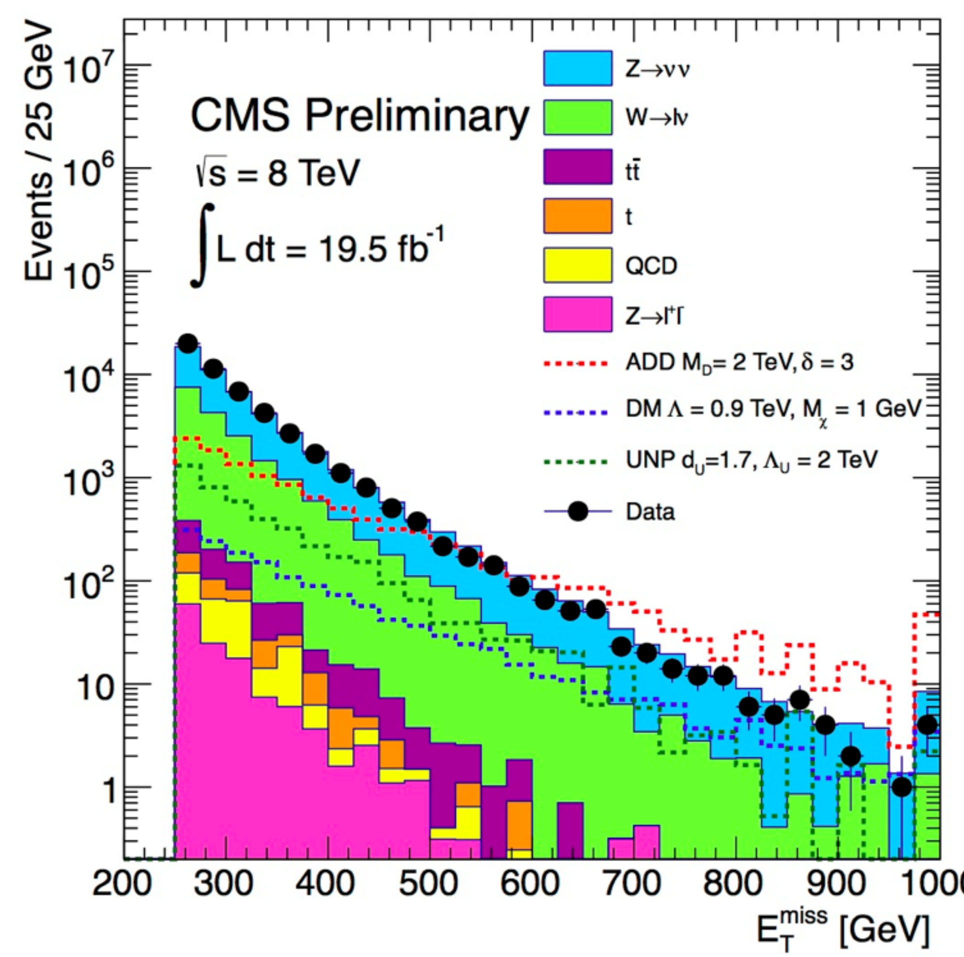




Mono-Jet Search

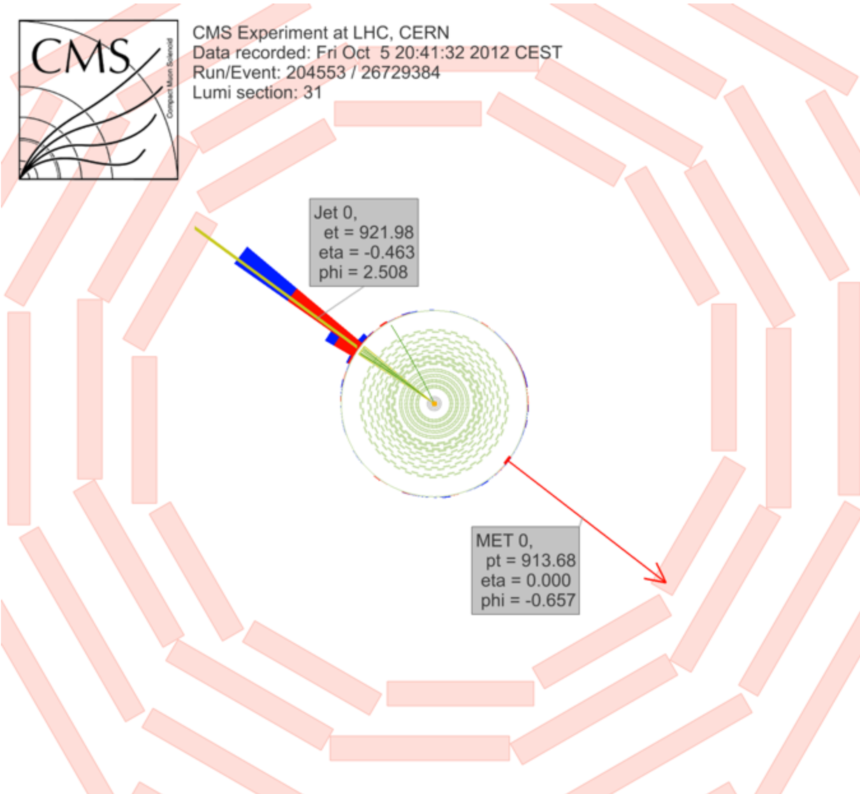
- Pair produced Dark Matter
  - missing energy and radiated jet(s)
  - similar strategy also for photons
- Event selection
  - leading jet p_T > ~120 GeV
  - topological cut to reduce QCD, e.g. opening of two jets
  - veto events with isolated leptons
- Background determination
  - mainly from data
    - Z(νν) + jets from measurement of Z + jets
    - W(lν) + jets from measurement of W + jets
  - MC only for very small backgrounds
    - ttbar, QCD, non-collision
- Count events with MET > 350-400 GeV



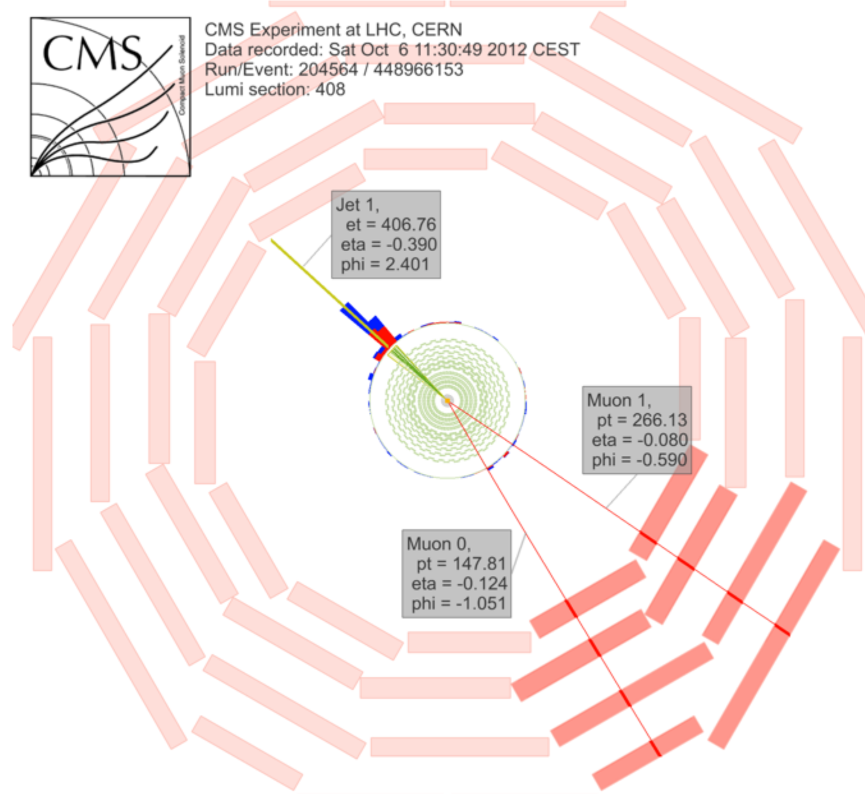


BACKGROUNDS

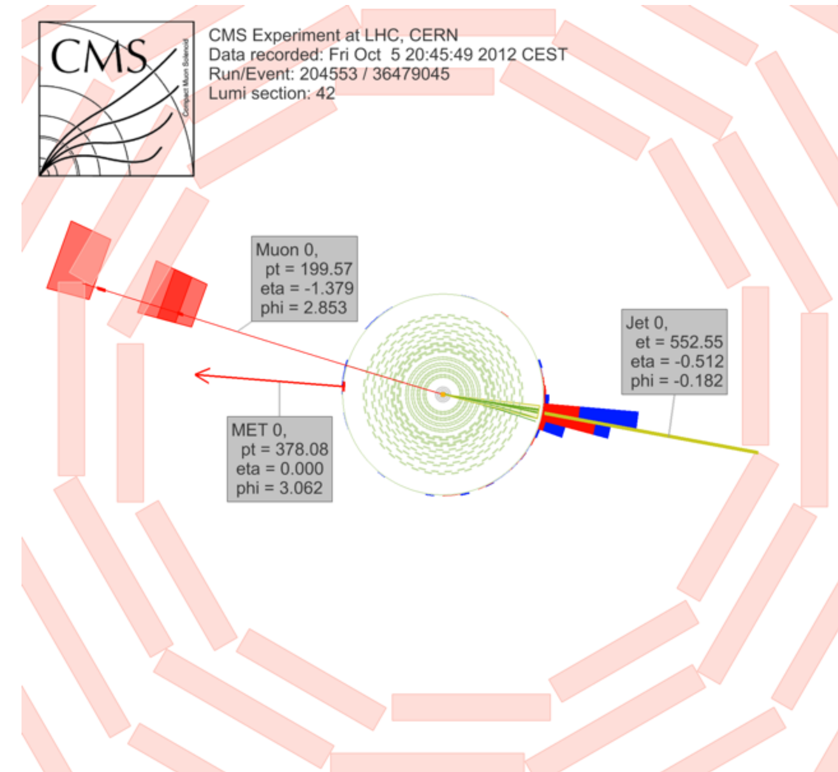
Signal



Z(νν)+jets: ~65% estimated from data



W(lν)+jets: ~30% estimated from data



Background Composition

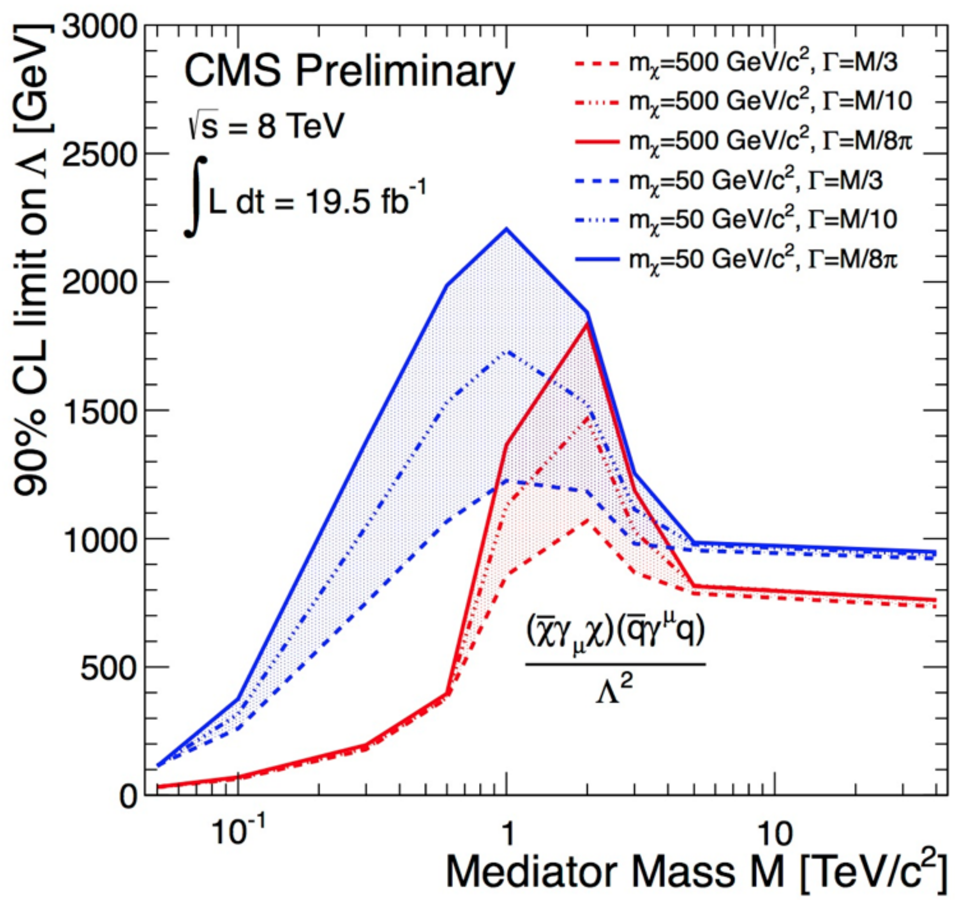
E_T^{miss} (GeV) →	> 250	> 300	> 350	> 400	> 450	> 500	> 550
$Z(\nu\nu)$+jets	30600 ± 1493	12119 ± 640	5286 ± 323	2569 ± 188	1394 ± 127	671 ± 81	370 ± 58
W+jets	17625 ± 681	6042 ± 236	2457 ± 102	1044 ± 51	516 ± 31	269 ± 20	128 ± 13
$t\bar{t}$	470 ± 235	175 ± 87.5	72 ± 36	32 ± 16	13 ± 6.5	6 ± 3.0	3 ± 1.5
$Z(\ell\ell)$+jets	127 ± 63.5	43 ± 21.5	18 ± 9.0	8 ± 4.0	4 ± 2.0	2 ± 1.0	1 ± 0.5
Single t	156 ± 78.0	52 ± 26.0	20 ± 10.0	7 ± 3.5	2 ± 1.0	1 ± 0.5	0 ± 0
QCD Multijets	177 ±88.5	76 ±38.0	23 ±11.5	3 ±1.5	2 ±1.0	1 ± 0.5	0 ± 0
Total SM	49154 ± 1663	18506 ± 690	7875 ± 341	3663 ± 196	1931 ± 131	949 ± 83	501 ± 59
Data	50419	19108	8056	3677	1772	894	508

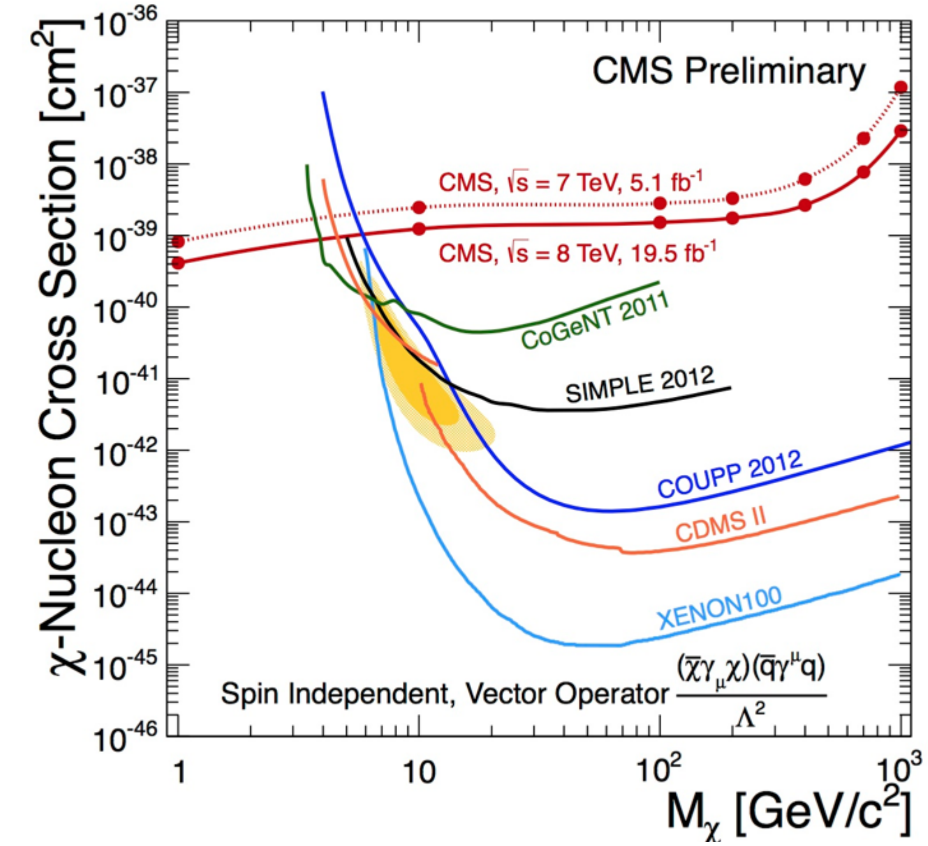
Systematic Uncertainty

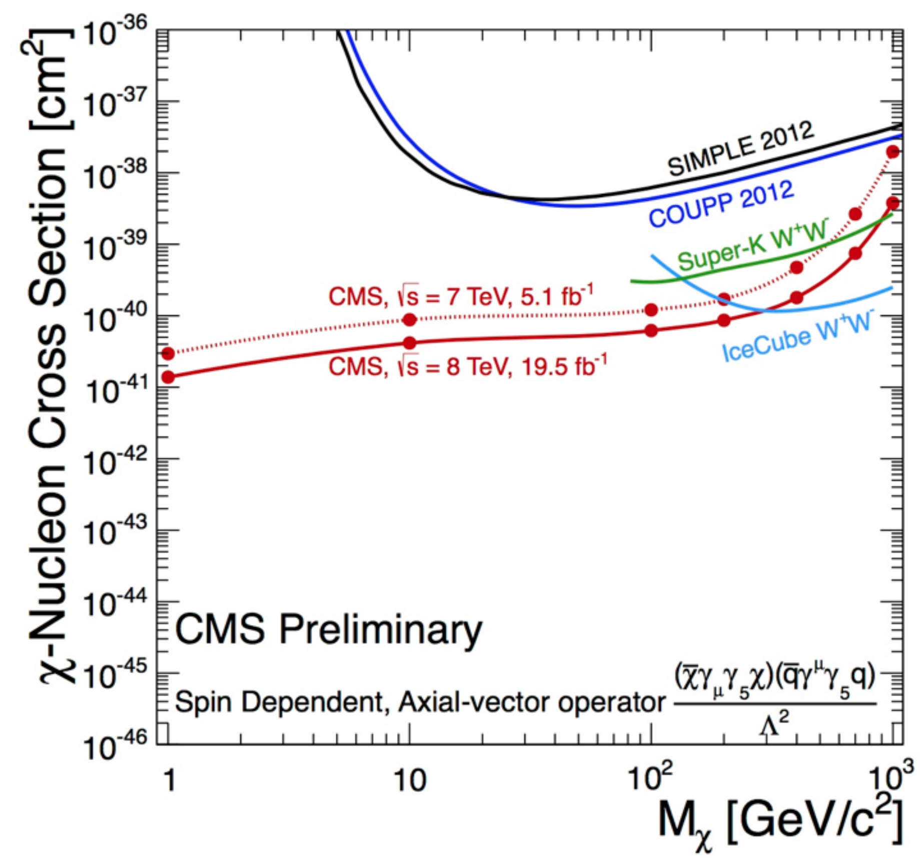
E_T^{miss} (GeV)	> 250	> 300	> 350	> 400	> 450	> 500	> 550
Statistics (N^{obs})	1.7	2.6	3.9	5.6	7.6	10.9	14.6
Background (N^{bgd})	0.8	0.6	0.8	0.2	0.0	0.0	0.0
Acceptance (A)	2.0	2.0	2.0	2.1	2.1	2.2	2.4
Selection efficiency (ϵ)	2.0	2.0	2.1	2.2	2.4	2.7	3.1
Total	4.5	4.9	5.8	7.1	8.9	12.1	15.6

SUMMARY OF DM LIMITS

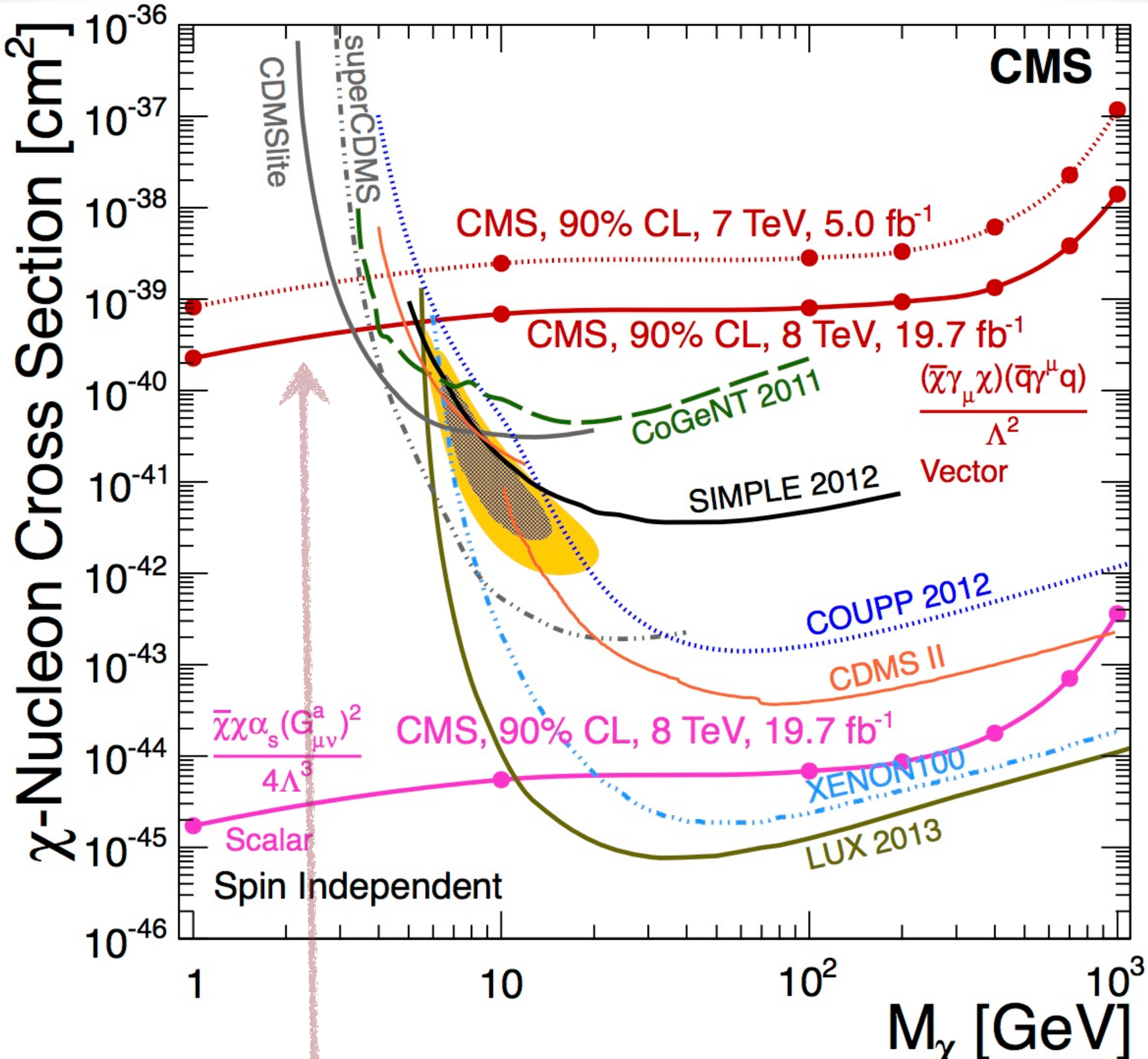
- Several orders of magnitude in mass explored by two searches
- Search at LHC sensitive to low mass region < 10 GeV not yet probed by direct detection experiments





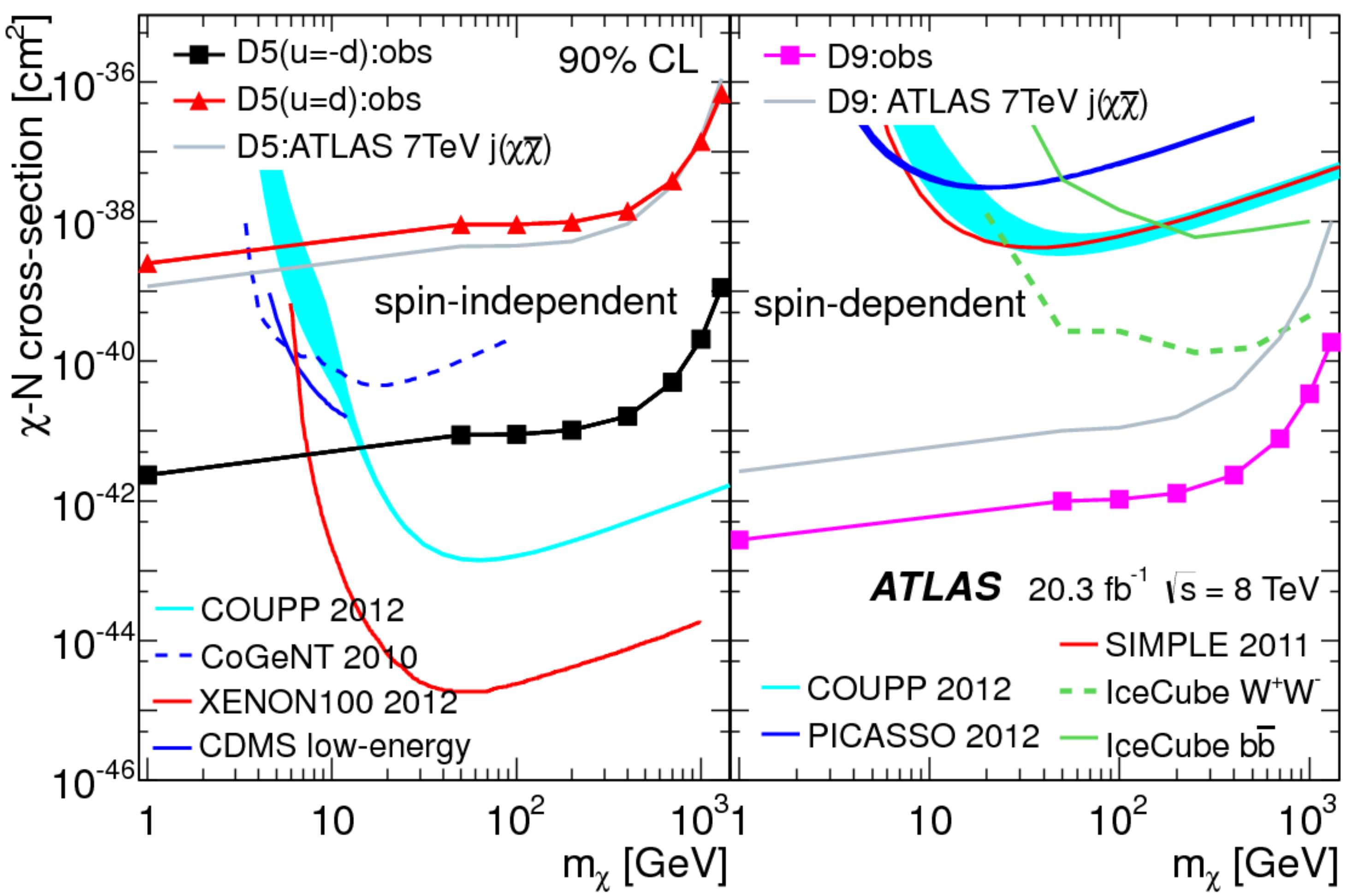


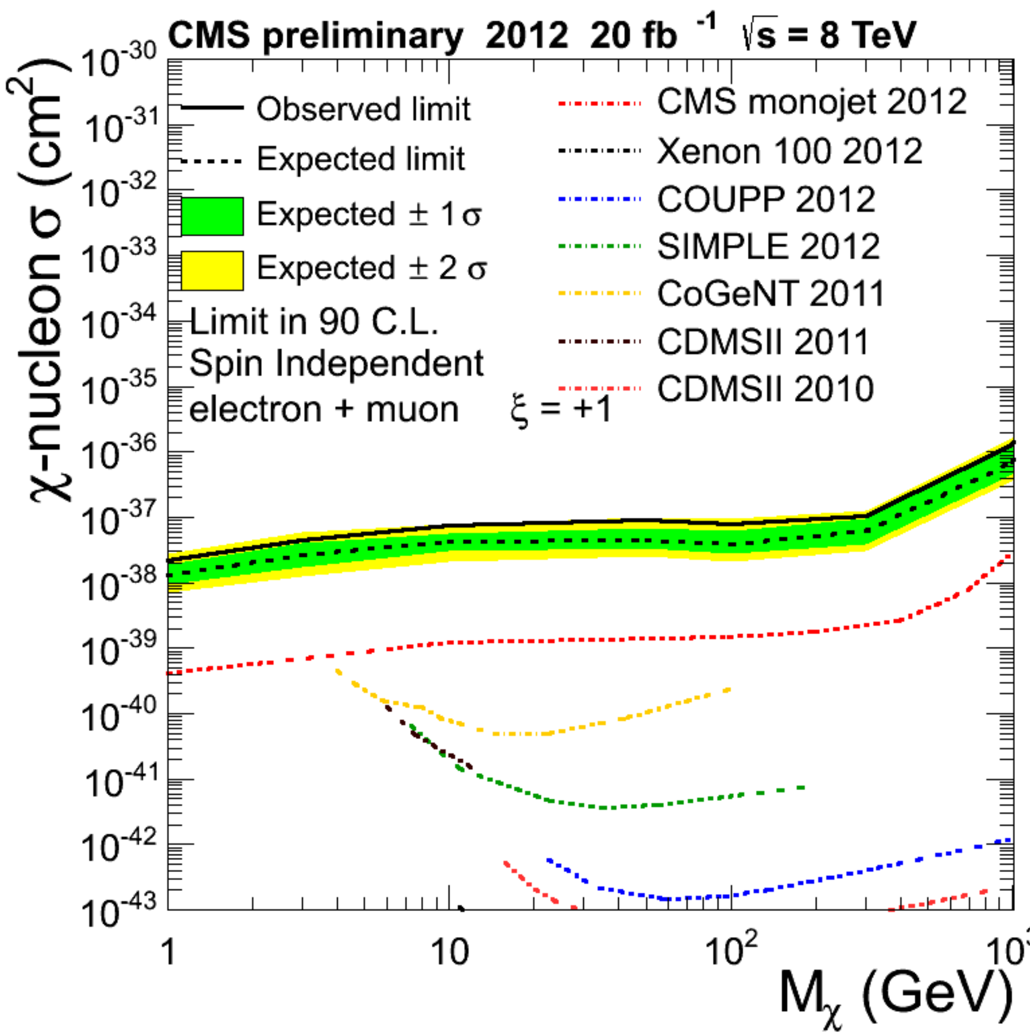
Dark Matter Exclusion



- *Search at LHC complementary to direct searches at low mass*

MONO-LEPTON VS MONOJET





PROSPECTS

- Standard Model of Particle Physics describes only 5% of the mass in the Universe
  - No Dark Matter candidate in Standard Model
- Multiple and complementary approaches under study to understand nature of Dark Matter
  - Indirect detection on Earth and in Space
  - Direct detection underground
  - Pair production at Large Hadron Collider
- Few potential signals have been observed
  - lacking independent confirmation by other detectors/techniques
- *Exciting times to participate in one of the most important open questions of our time*

REFERENCES

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- Monophoton
  - ATLAS: http://cdsweb.cern.ch/record/1460397
  - CMS: http://arxiv.org/abs/1204.0821
- Mono-Lepton
  - ATLAS: http://arxiv.org/abs/1309.4017
  - CMS: http://cds.cern.ch/record/1563245
- Recent results on direct Dark Matter searches
  - https://agenda.infn.it/conferenceDisplay.py?confId=6943