Recent Results in Dark Matter Experiments

- **Evidence and Candidates of Dark Matter**
- **Direct and Indirect Searches of WIMPs**
- **PAMELA/ATIC /DAMA Anomalous Results**
- **TEXONO Results on Low Mass WIMPs**

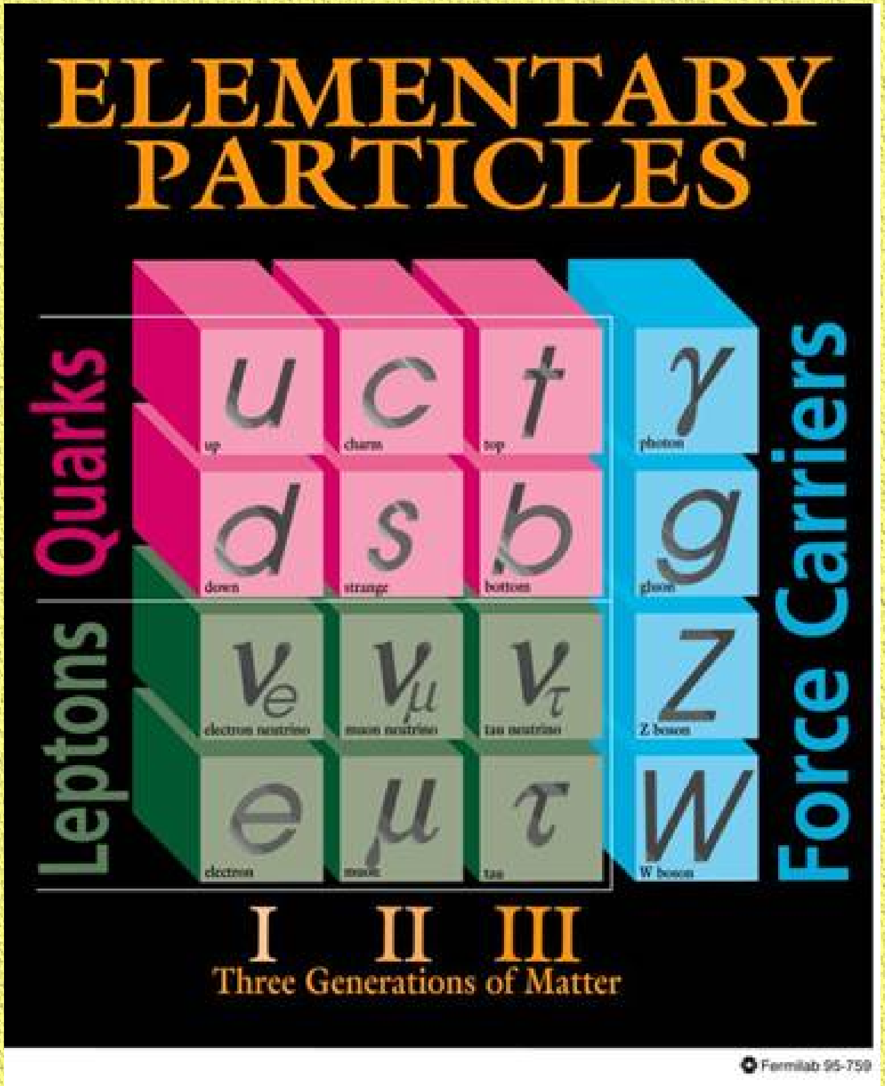
Henry T. Wong / 王子敬

April 2009 @

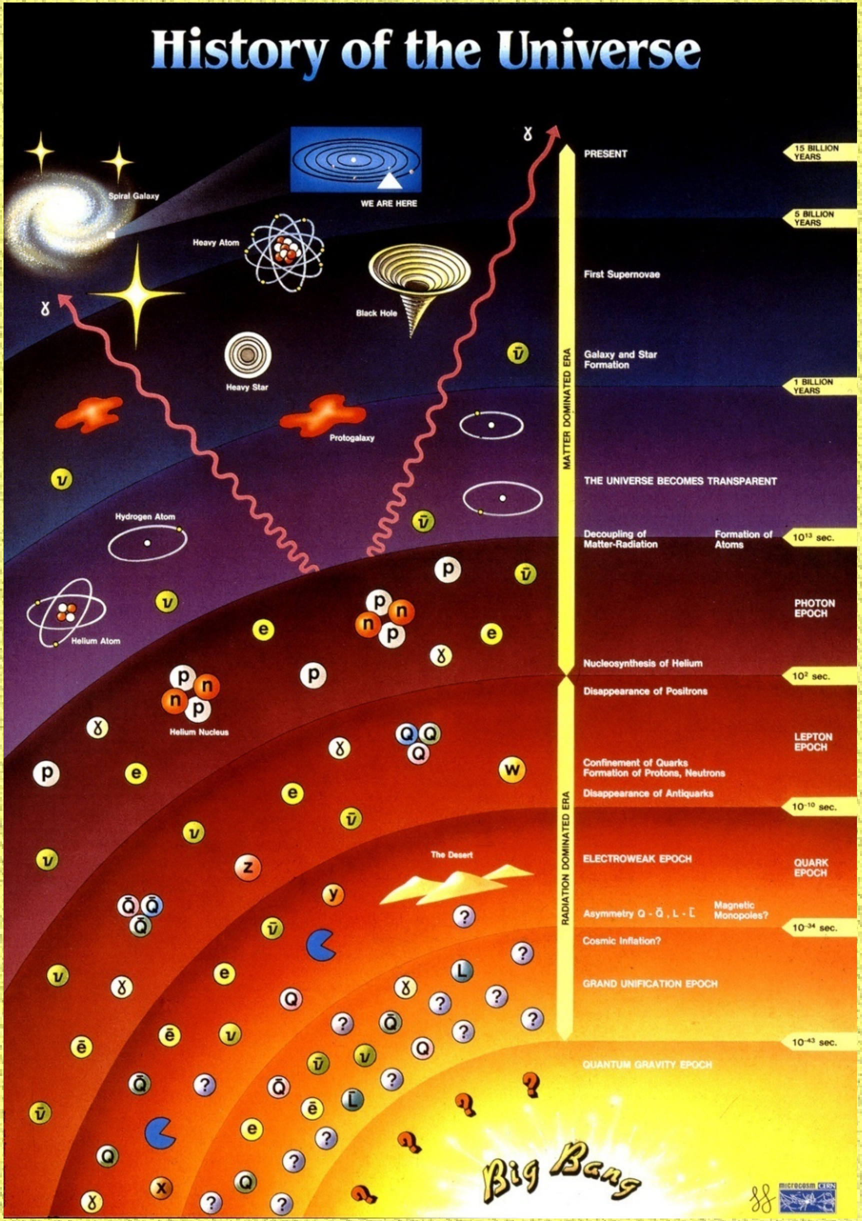
中央研究院物理研究所
INSTITUTE OF PHYSICS ACADEMIA SINICA

國立清華大學物理系
Department of Physics
National Tsing Hua University

Standard Model of Particle Physics and Cosmology

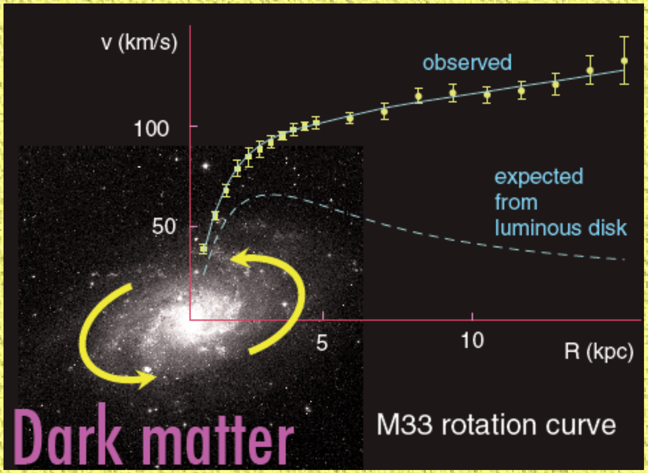


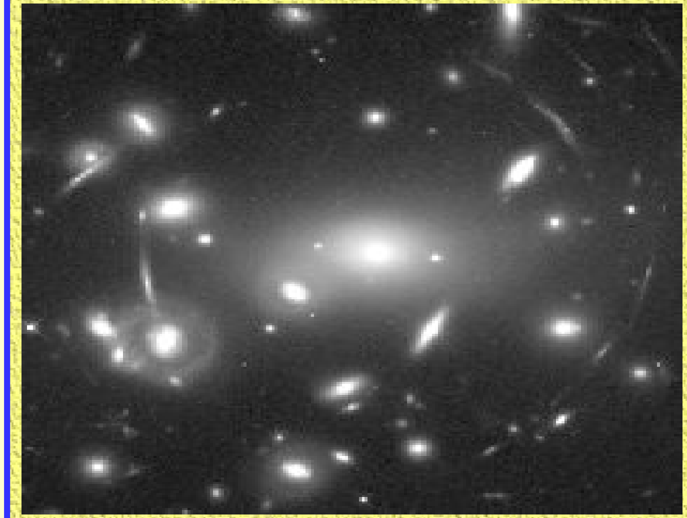
+ H

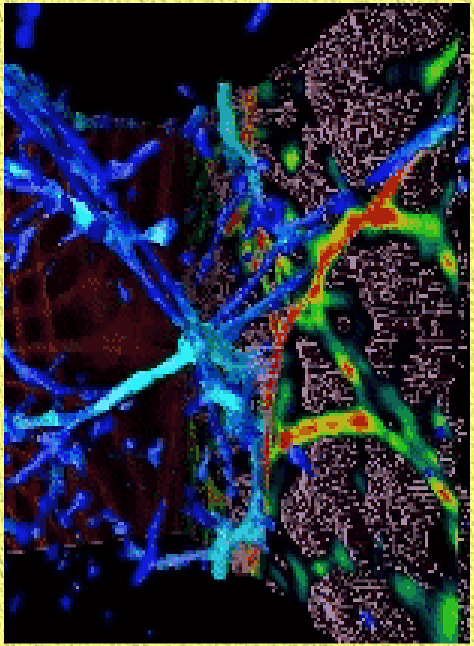


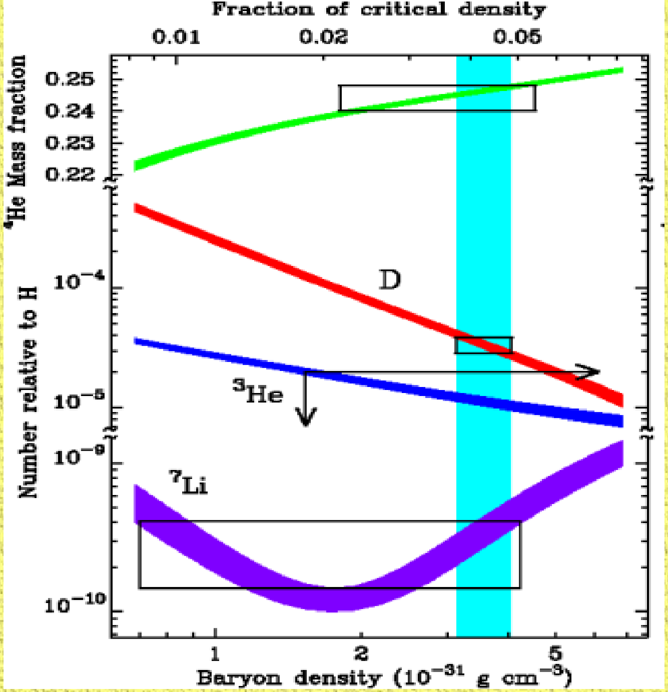
Evidence for Dark Matter

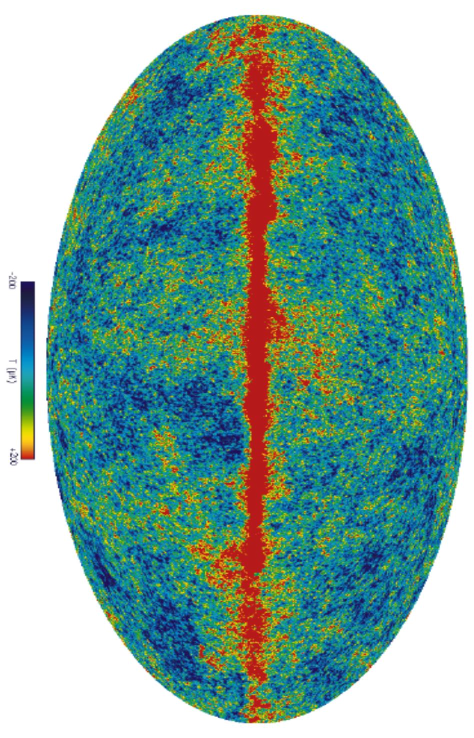
- **Spiral galaxies**
  - ↳ Rotation Curve
    - ⇒ Missing Ω (Galactic)
- **Clusters & Superclusters**
  - ↳ Gravitational Lensing
    - ⇒ Missing Ω (Cluster)
- **Large Scale Structures**
  - ⇒ Cold Dark Matter
- **CMB Anisotropy**
  - ⇒ Ω_{total} ; Ω_{baryon} (cosmological)
- **Big Bang Nucleosynthesis**
  - ⇒ Constrain Baryon density

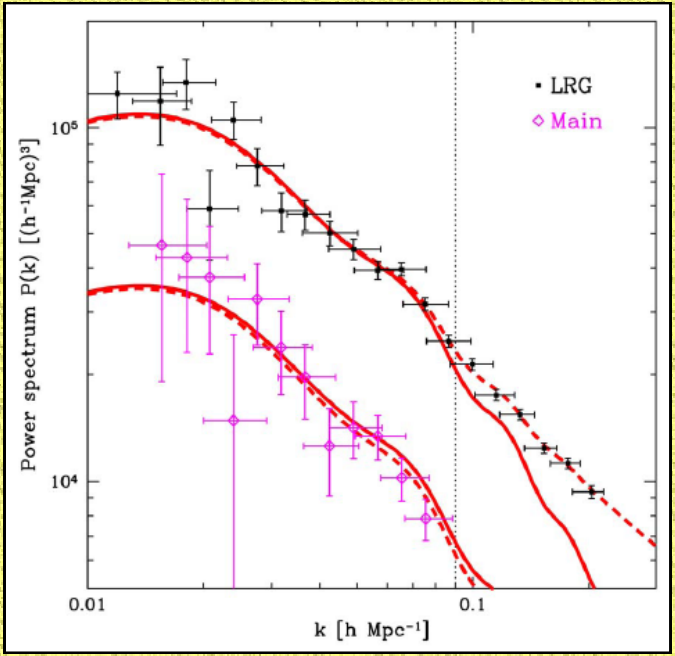


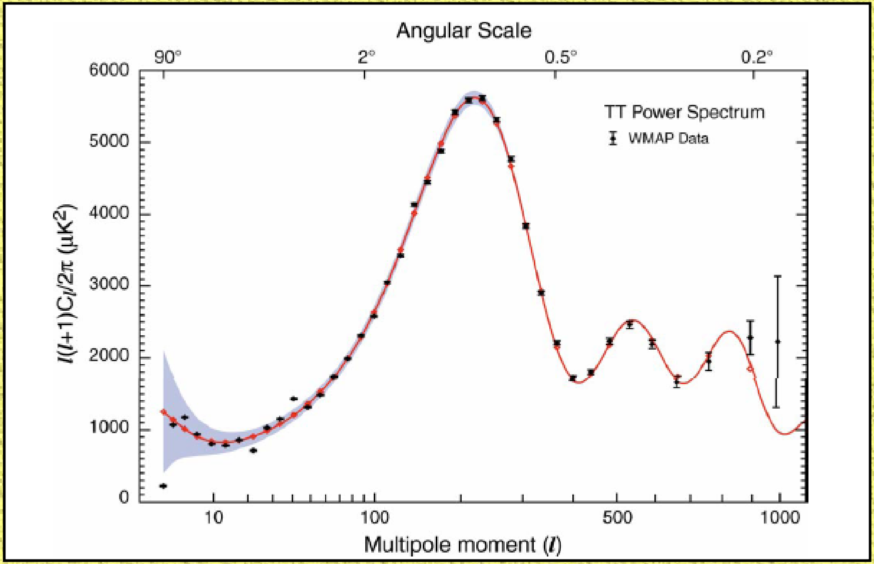





Fraction of critical density
0.01
0.02
0.05
^{4}He Mass fraction
0.25
0.24
0.23
0.22
Number relative to H
10^{-4}
10^{-5}
10^{-9}
10^{-10}
D
^{3}He
^{7}Li
1
2
5
Baryon density (10^{-31} g cm^{-3})

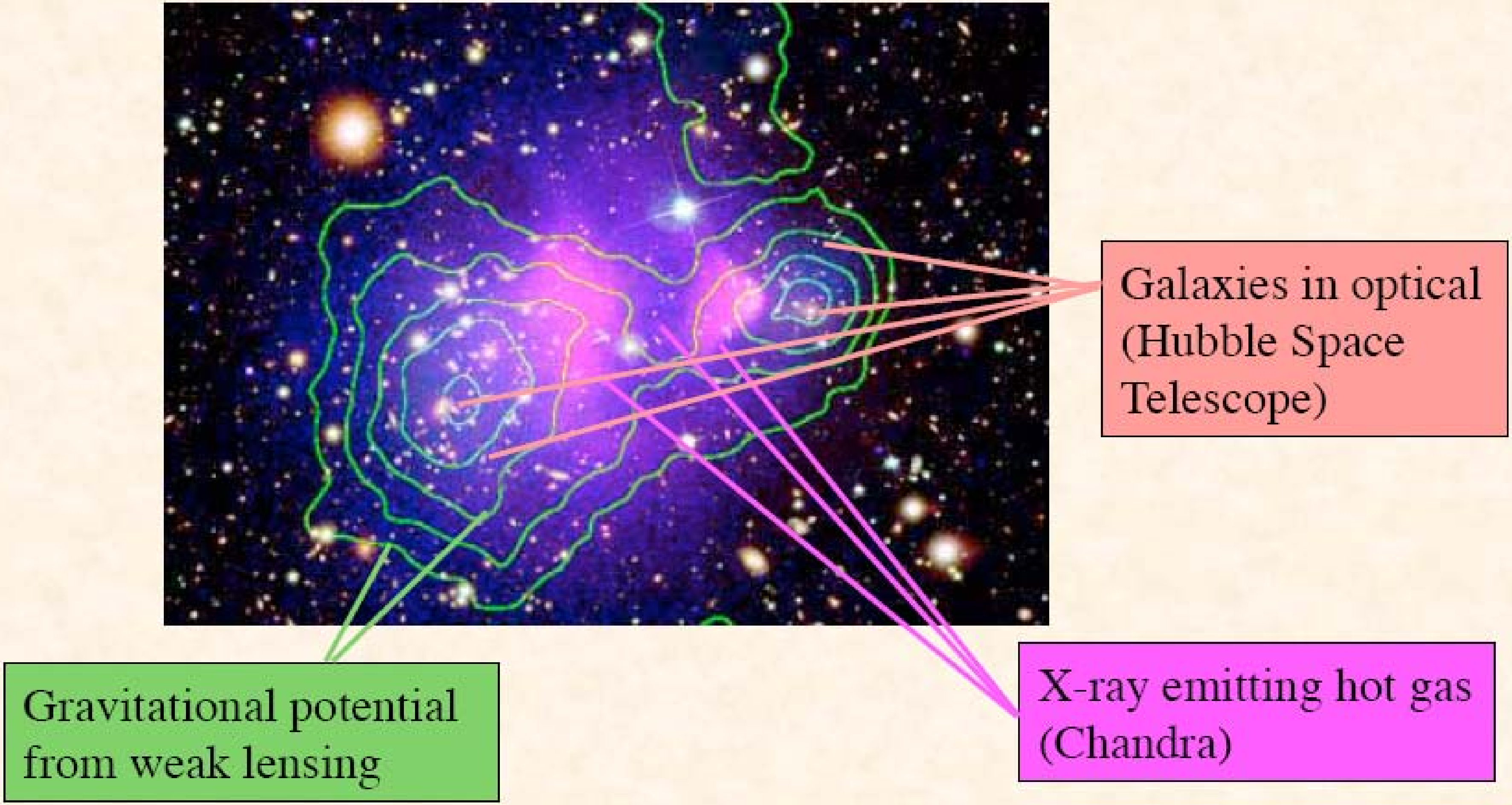

-200
T (μK)
+200


▪ LRG
◇ Main
10^5
10^4
Power spectrum P(k) [(h^{-1}Mpc)^3]
0.01
0.1
k [h Mpc^{-1}]


Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK^2)
TT Power Spectrum
WMAP Data
10
100
500
1000
Multipole moment (l)

Dark Matter is DARK (not interacting electromagnetically)

And NOT modified Gravity …….

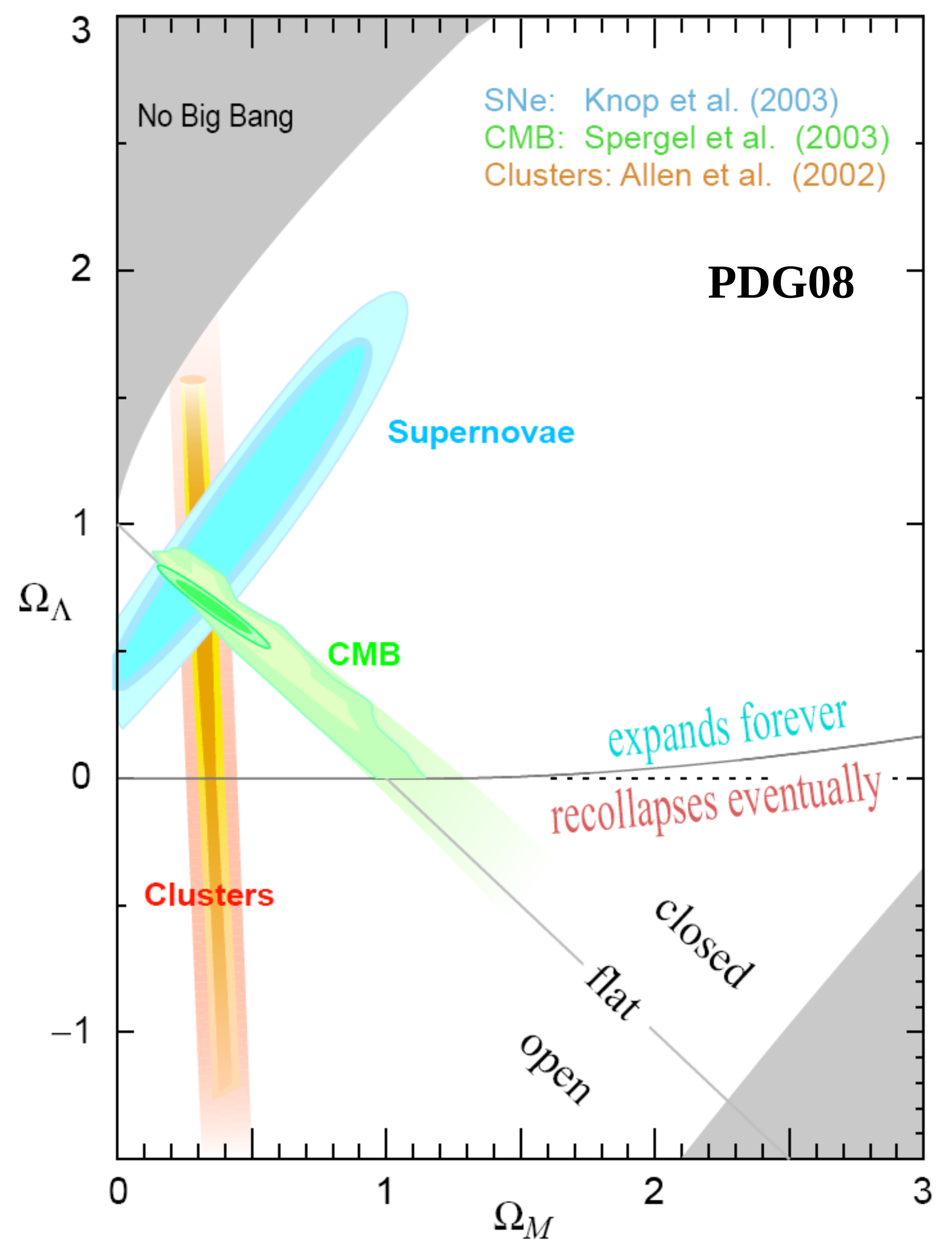


Galaxies in optical (Hubble Space Telescope)

Gravitational potential from weak lensing

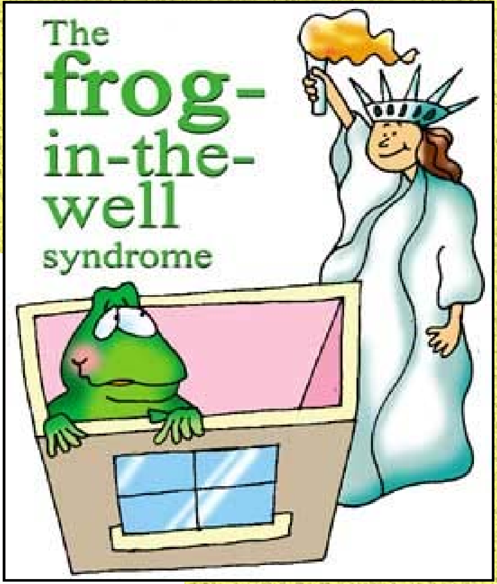
X-ray emitting hot gas (Chandra)

Combined Constraints :

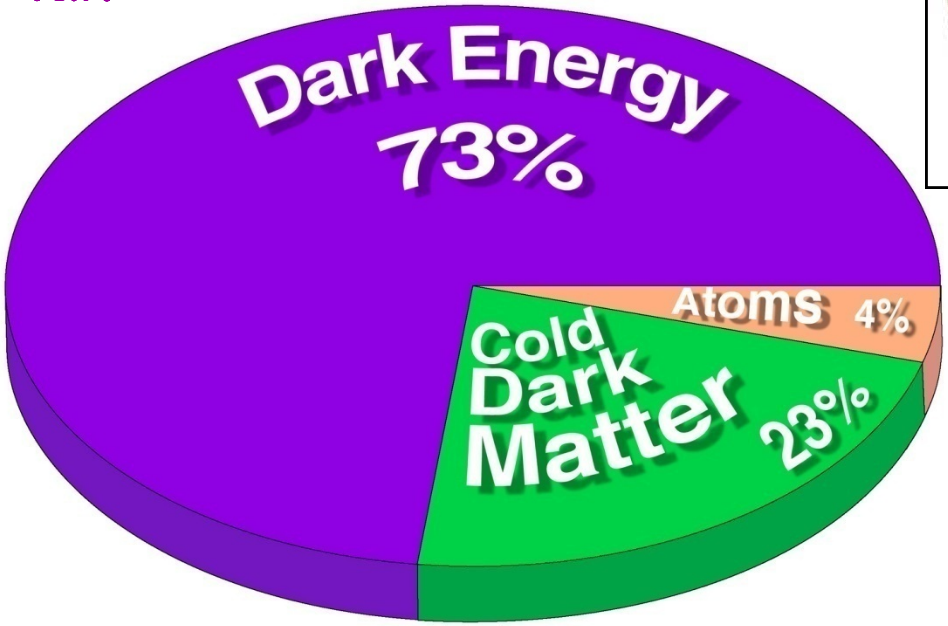


$$\Omega_\Lambda = 0.73 \pm 0.04, \qquad \Omega_m = 0.27 \pm 0.04$$

Compositions of the Universe : We only Understand ~4% !!!????



Dark Energy : " We know less than Nothing !"



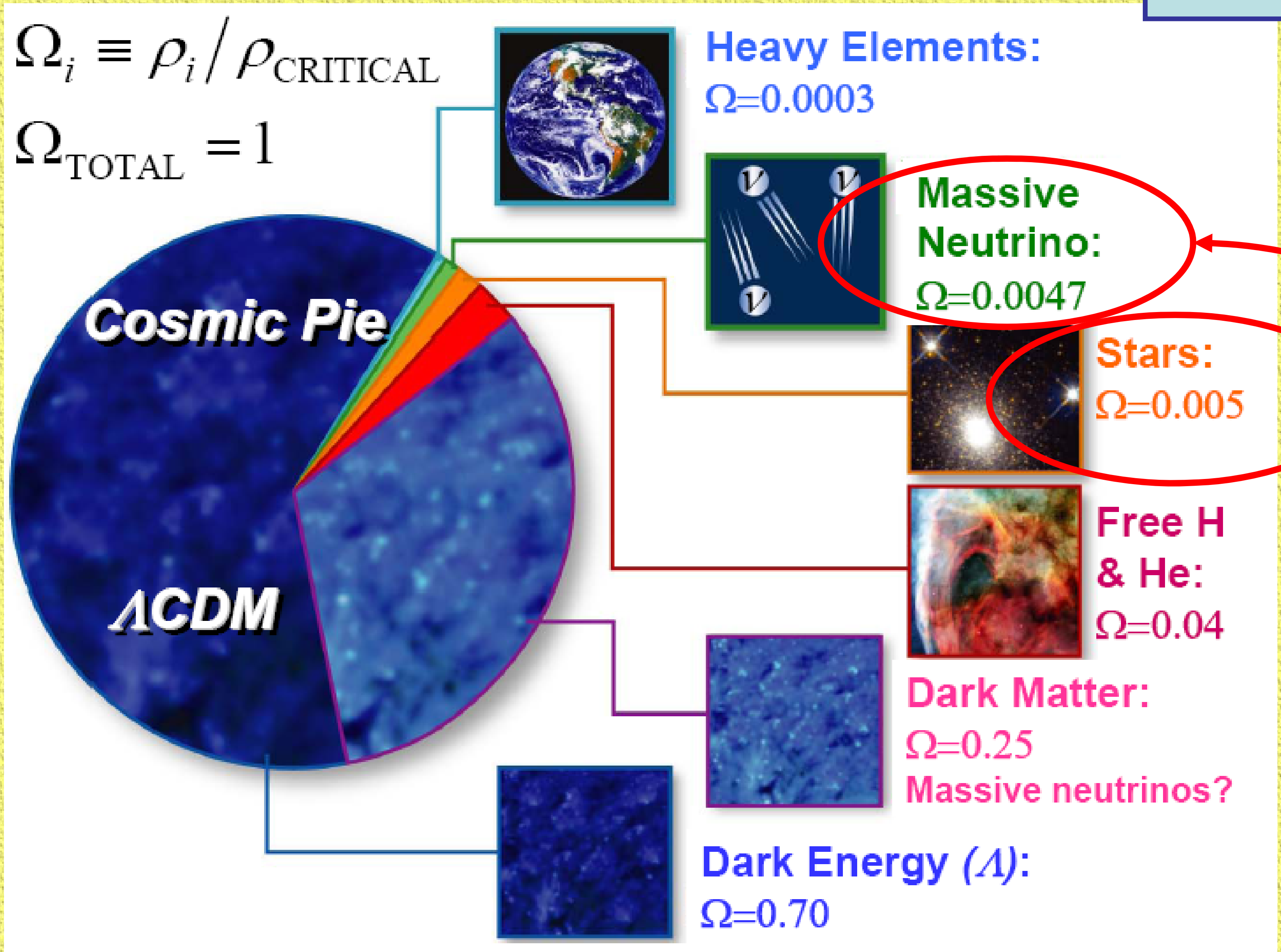
← **Standard Model Matter** : Understood

Dark Matter : " We know Nothing !" (but perhaps have reasonable guesses)

Or ….

- *The Ultimate Copernicus Principle !!*

at least as much neutrinos by mass as visible matter !



$$\Omega_i \equiv \rho_i / \rho_{\mathrm{CRITICAL}}$$

$$\Omega_{\mathrm{TOTAL}} = 1$$

Heavy Elements:
$\Omega=0.0003$

Massive Neutrino:
$\Omega=0.0047$

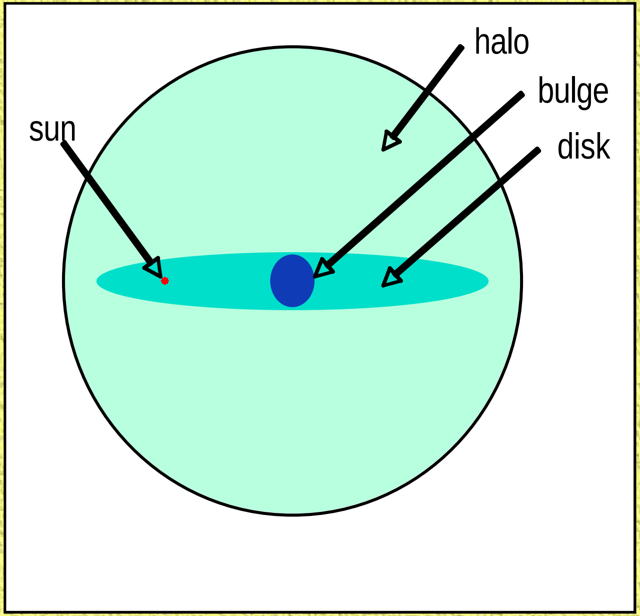
Stars:
$\Omega=0.005$

Free H & He:
$\Omega=0.04$

Dark Matter:
$\Omega=0.25$
Massive neutrinos?

Dark Energy (*Λ*):
$\Omega=0.70$

Properties of a Good Cold Dark Matter Candidates:

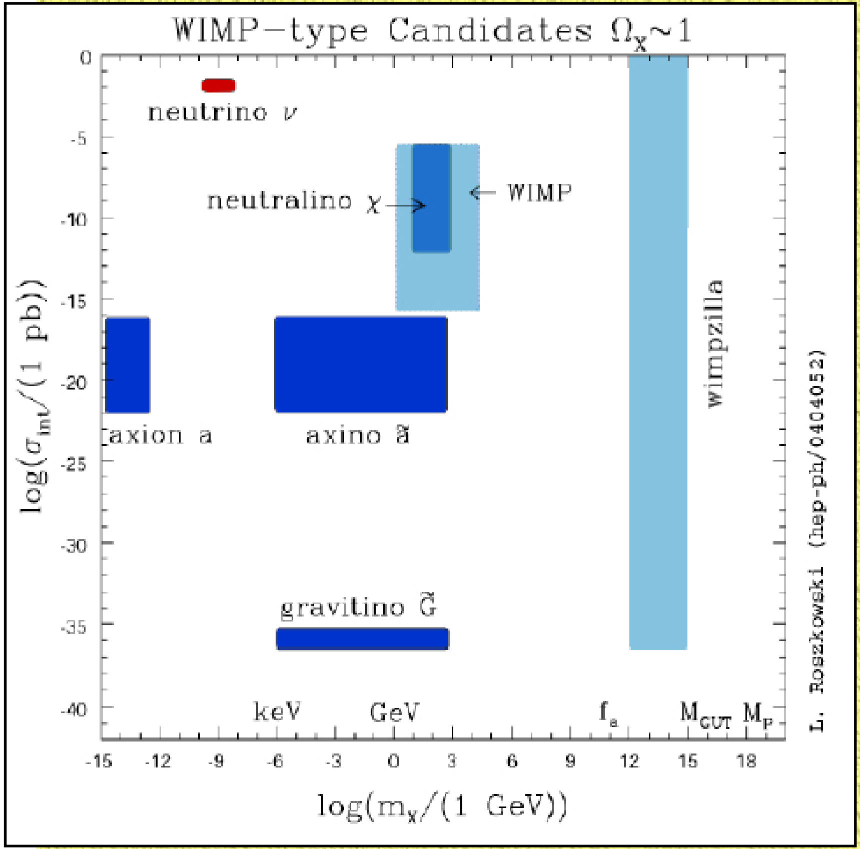


Dark Matter gravitationally bounded in galactic halo

- ✓ stable (protected by a conserved quantum number)
- ✓ no charge, no colour (weakly interacting)
- ✓ cold, non dissipative
- ✓ relic abundance compatible to observation
- ✓ motivated by theory (vs. “ad hoc”)

(Incomplete) List of CDM candidates

- RH neutrinos
- *Axions*
- Lightest Supersymmetric particle (LSP) – neutralino, sneutrino, axino
- Lighest Kaluza-Klein Particle (LKP)
- Heavy photon in Little Higgs Models
- Solitons (Q-balls, B-balls)
- Black Hole remnants
- …



Evolution of the Dark Matter Density

- Produced in big bang, but also annihilate with each other.
- Annihilation stops when number density drops to the point that

$$\boxed{H > \Gamma_A \approx n_\chi < \sigma_A \mathrm{v} >}$$

i.e. annihilation too slow to keep up with Hubble expansion ("freeze out")

- Leaves a relic abundance:

$$\boxed{\Omega_\chi h^2 \approx 10^{-27} cm^3 s^{-1} / < \sigma_A \mathrm{v} >_{\mathrm{fr}}}$$

! *IF* **σ_A ~ electroweak scale**

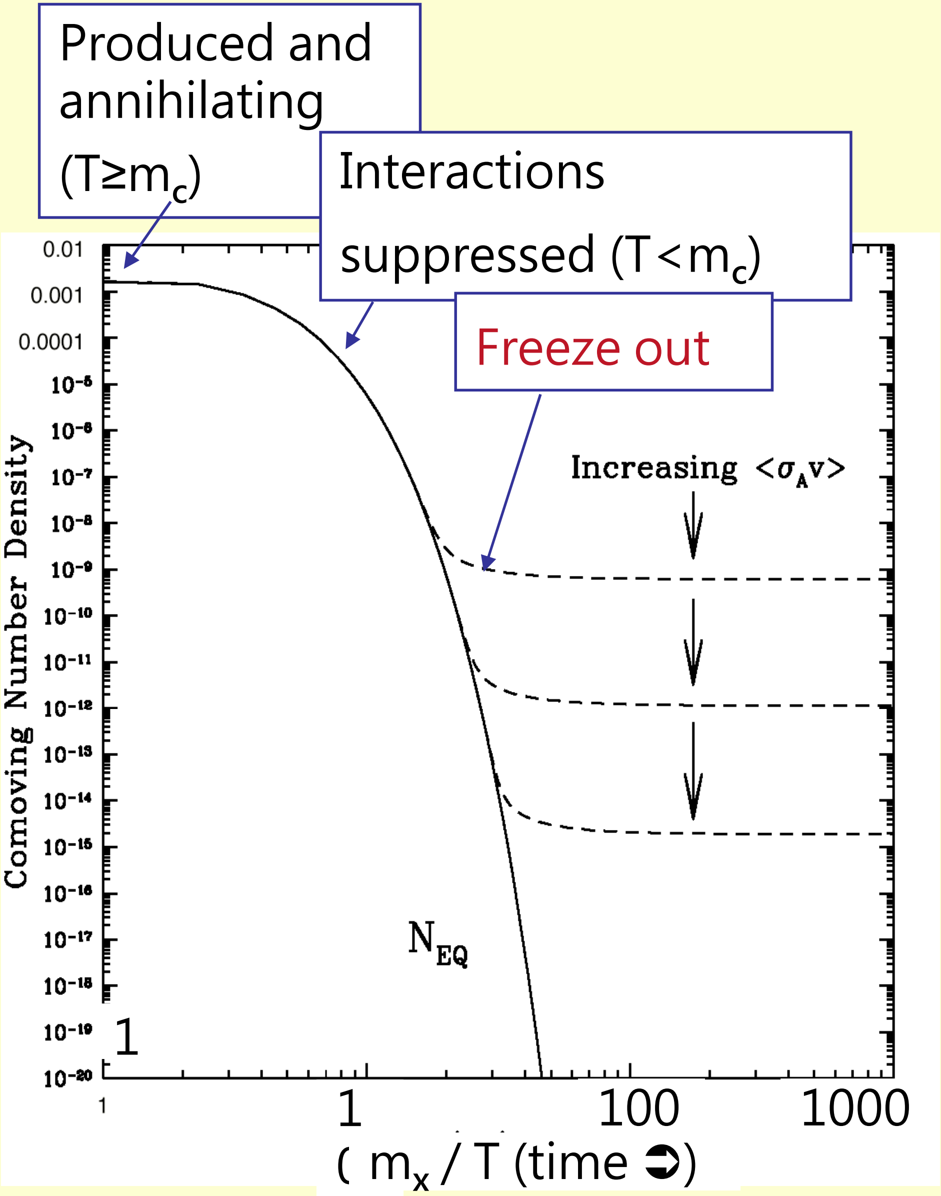
$$\boxed{\sigma_{ann.} \approx \text{a few pb} \approx \alpha_W^2 / M_W^2}$$

THEN $\boxed{\Omega_\chi \sim 0.3}$

[coincidence or miracle ?!]

$\Rightarrow$ ***WIMPs***

(no constraints on m_χ)

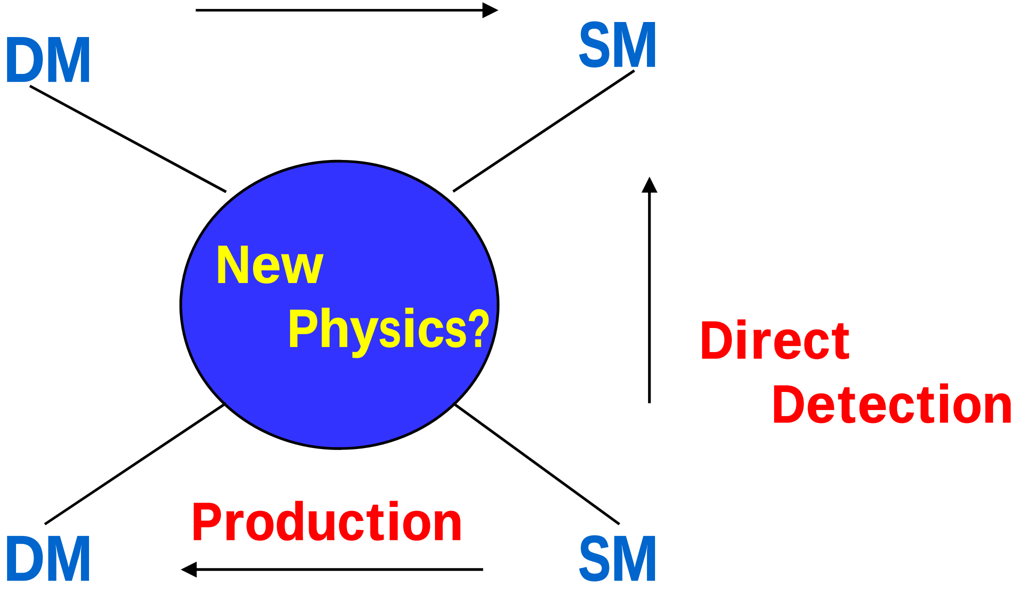


Produced and annihilating ($T \geq m_c$)

Interactions suppressed ($T < m_c$)

Freeze out

Dark Matter Detection



Indirect Detection

DM

SM

New Physics?

Direct Detection

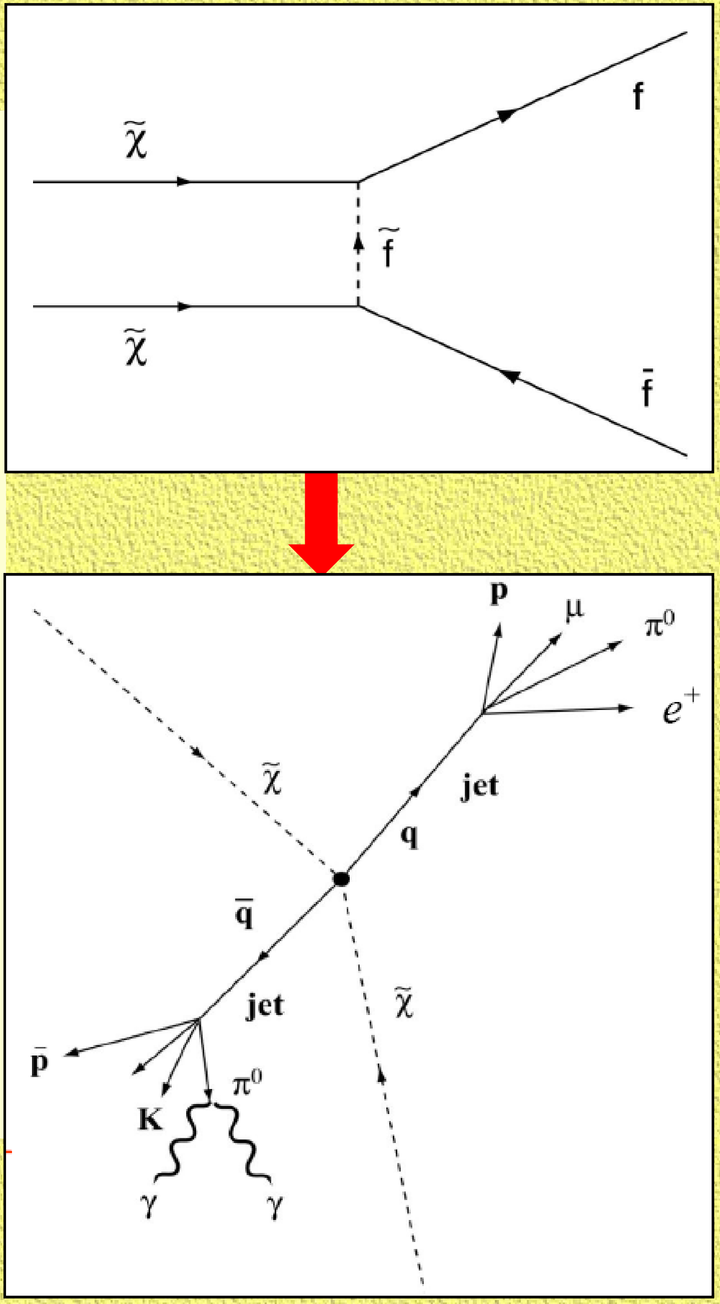
Production

DM

SM

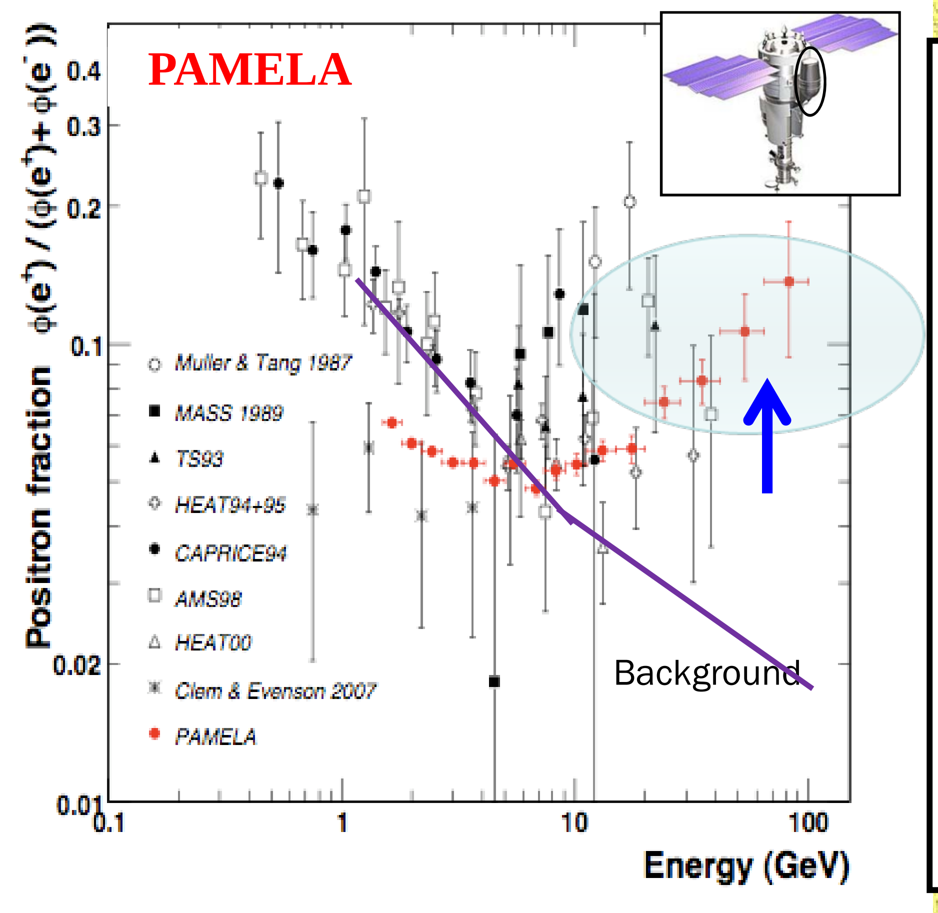
Indirect Detection of WIMP

- through their annihilation products
- Signals ⇨ high-energy neutrinos, anti-protons, positrons & photons
- Sources ⇨ Sun, Earth, Galactic Center, Milky Way Halo, Stars, External Galaxies
- HE neutrinos from Sun/Earth or anomalous γ-rays peaks ⇨ smoking gun signatures
- Anomalous spectral distributions of e^+, p-bar, γ etc. ⇨ dependent on background models



Anomalous Cosmic Positron Spectrum

！ Consolidated by latest results from PAMELA, PPB-BETS, ATIC



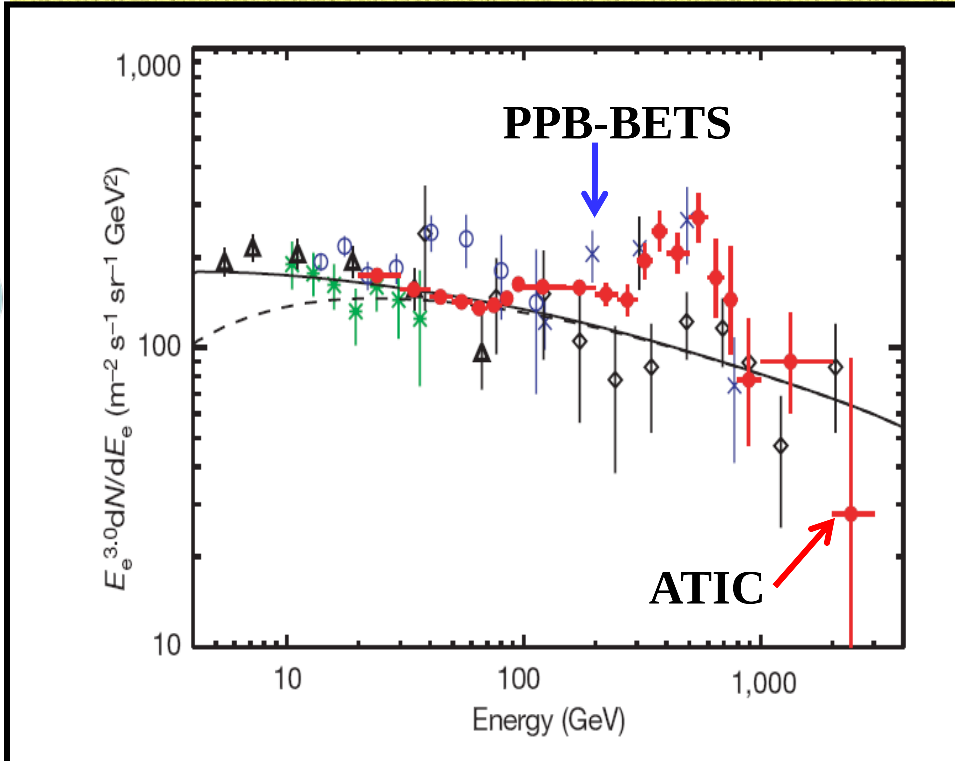


Figure 3 | ATIC results showing agreement with previous data at lower energy and with the imaging calorimeter PPB-BETS at higher energy. Th

Astrophysical Primary sources or WIMP-induced ??

Cosmic-Ray Anti-proton from PAMELA is OK, however……

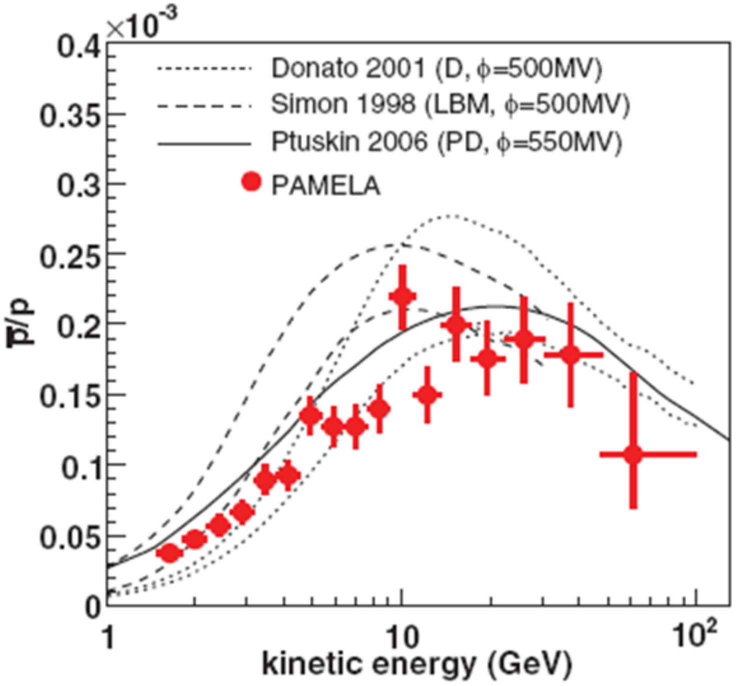


FIG. 3 (color). The antiproton-to-proton flux ratio obtained in this work compared with theoretical calculations for a pure secondary production of antiprotons during the propagation of cosmic rays in the galaxy. The dashed lines show the upper and lower limits calculated by Simon *et al.* [17] for the standard leaky box model, while the dotted lines show the limits from Donato *et al.* [18] for a Diffusion model with reacceleration. The solid line shows the calculation by Ptuskin *et al.* [19] for the case of a plain diffusion model. The curves were obtained using appropriate solar modulation parameters (indicated as ϕ) for the PAMELA data taking period.

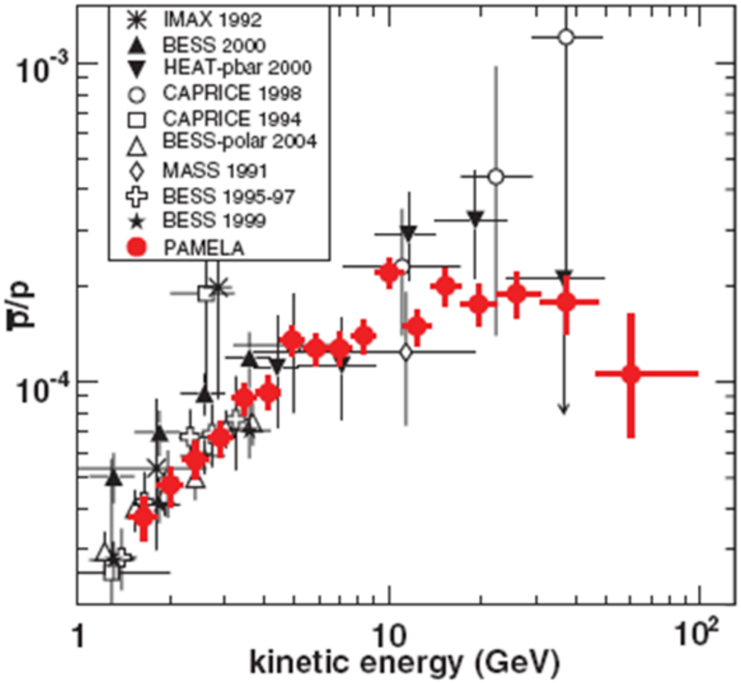


FIG. 4 (color). The antiproton-to-proton flux ratio obtained in this work compared with contemporary measurements [8–10,20–23].

Advanced Thin Ionization Calorimeter

ATIC

411

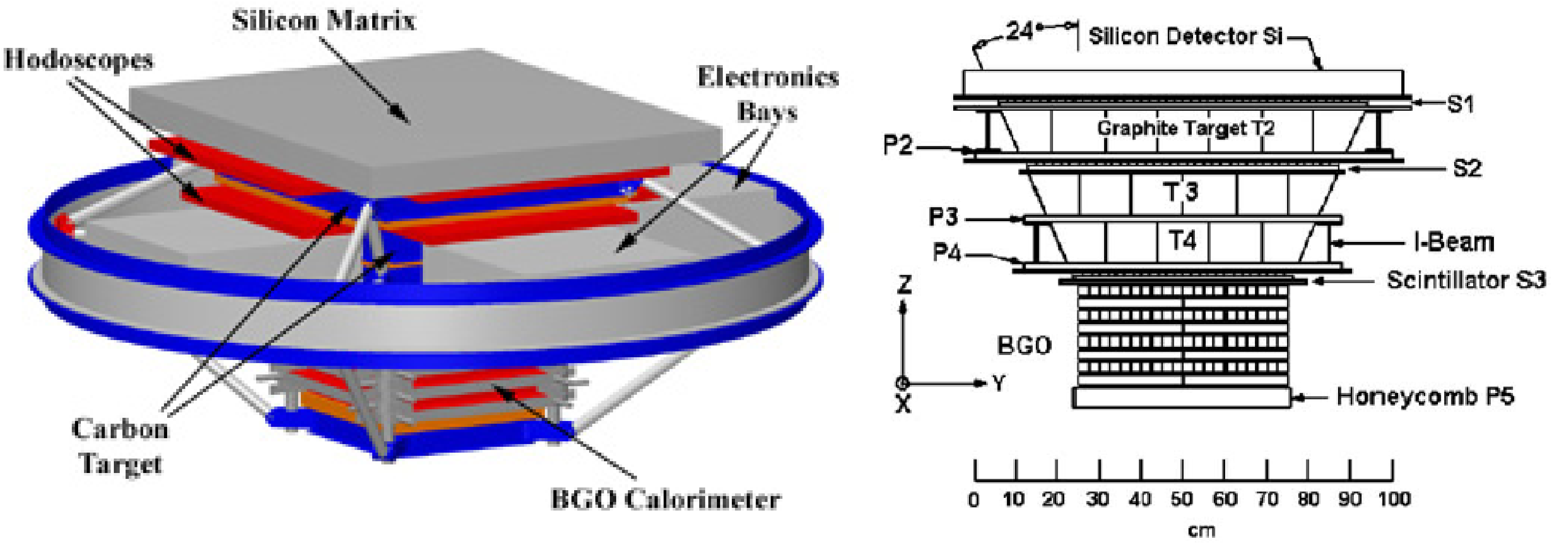


Fig. 1. 3D mechanical drawing (left) and 2D simulation s

Typical (p,e,γ) Shower image in ATIC (Flight data 250 GeV @ BGO)

- **Electron and gamma-ray showers are narrower than the proton shower**
- **Gamma-ray shower: No hits at top detectors around shower axis**
- **p-rejection in e ~ 10^{-4}**

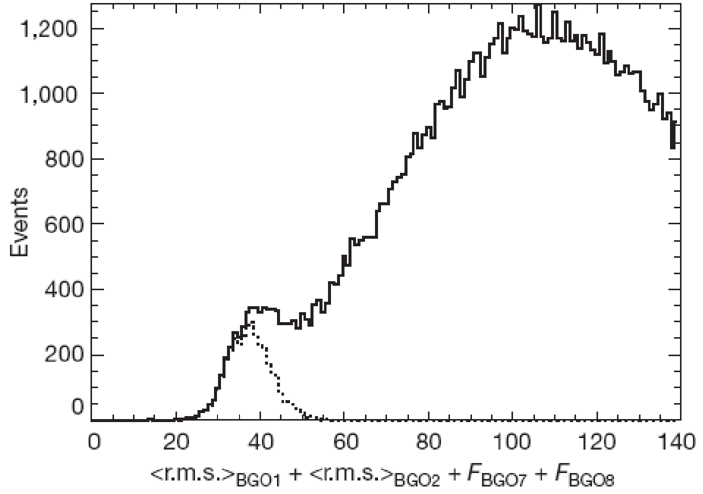
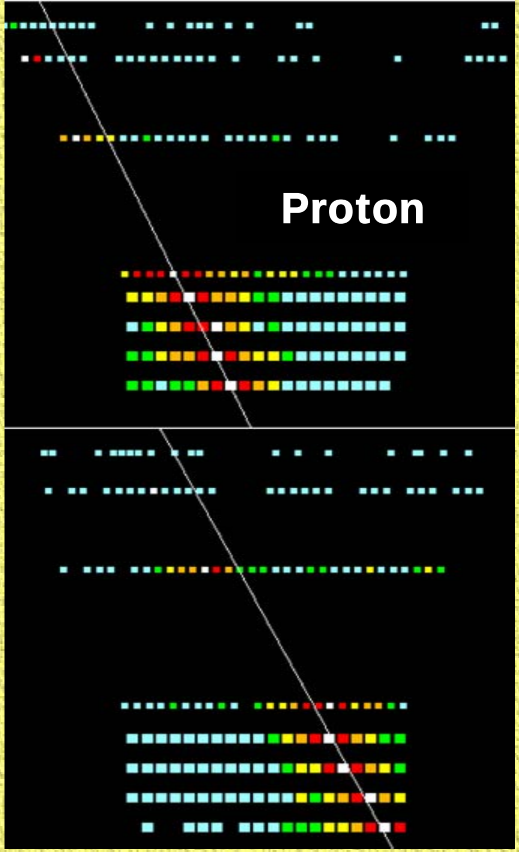
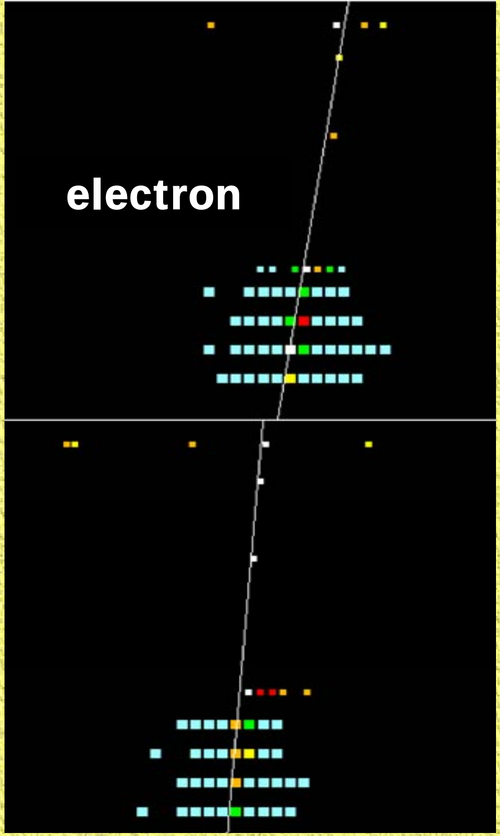
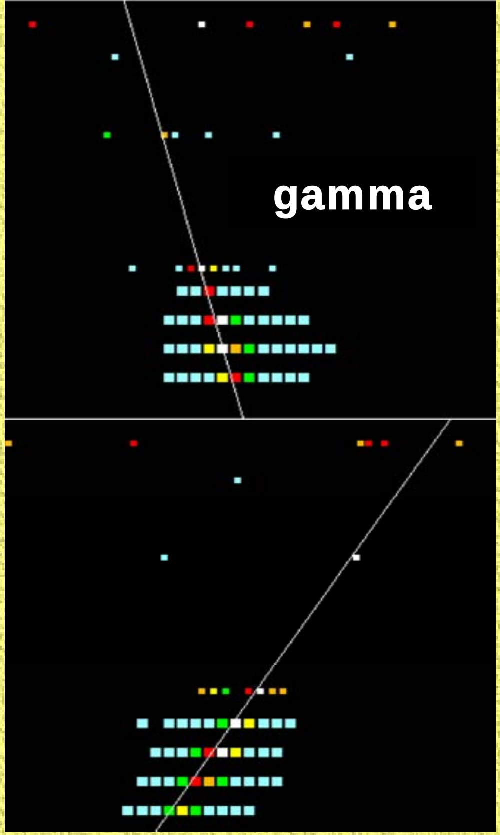
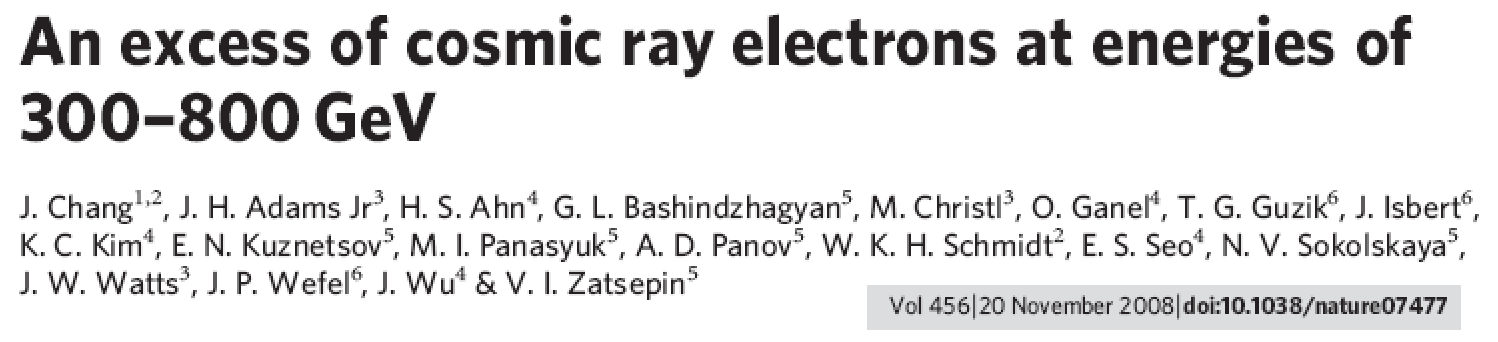


Figure 1 | Separation of electrons from protons in the ATIC instrument.





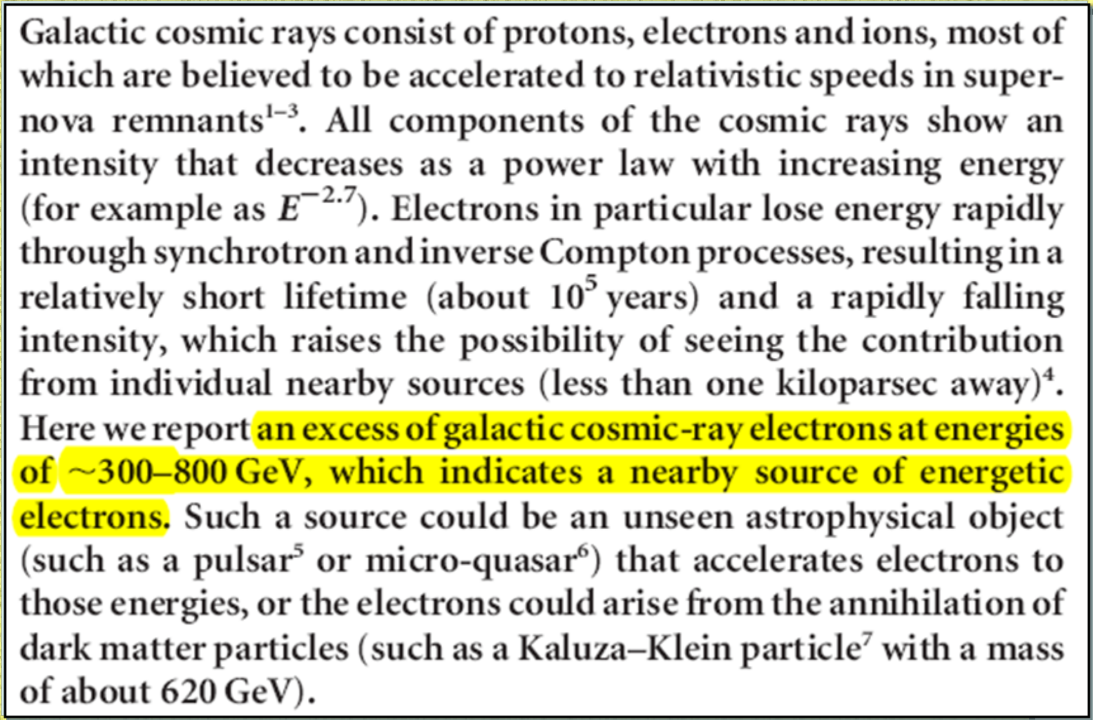




An excess of cosmic ray electrons at energies of 300–800 GeV

J. Chang[1,2], J. H. Adams Jr[3], H. S. Ahn[4], G. L. Bashindzhagyan[5], M. Christl[3], O. Ganel[4], T. G. Guzik[6], J. Isbert[6], K. C. Kim[4], E. N. Kuznetsov[5], M. I. Panasyuk[5], A. D. Panov[5], W. K. H. Schmidt[2], E. S. Seo[4], N. V. Sokolskaya[5], J. W. Watts[3], J. P. Wefel[6], J. Wu[4] & V. I. Zatsepin[5]

Vol 456|20 November 2008|**doi:10.1038/nature07477**



Galactic cosmic rays consist of protons, electrons and ions, most of which are believed to be accelerated to relativistic speeds in supernova remnants[1–3]. All components of the cosmic rays show an intensity that decreases as a power law with increasing energy (for example as $E^{-2.7}$). Electrons in particular lose energy rapidly through synchrotron and inverse Compton processes, resulting in a relatively short lifetime (about 10^5 years) and a rapidly falling intensity, which raises the possibility of seeing the contribution from individual nearby sources (less than one kiloparsec away)[4]. Here we report an excess of galactic cosmic-ray electrons at energies of ~300–800 GeV, which indicates a nearby source of energetic electrons. Such a source could be an unseen astrophysical object (such as a pulsar[5] or micro-quasar[6]) that accelerates electrons to those energies, or the electrons could arise from the annihilation of dark matter particles (such as a Kaluza–Klein particle[7] with a mass of about 620 GeV).

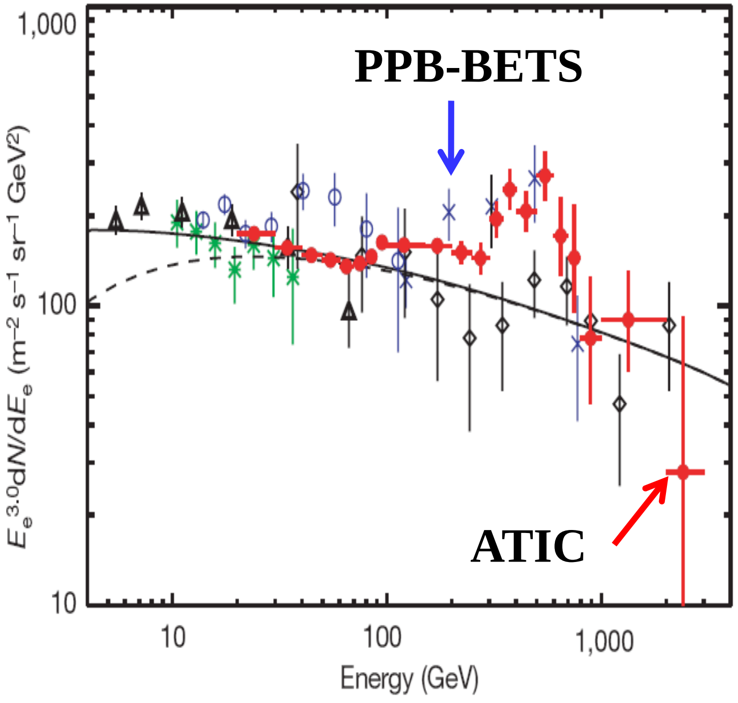
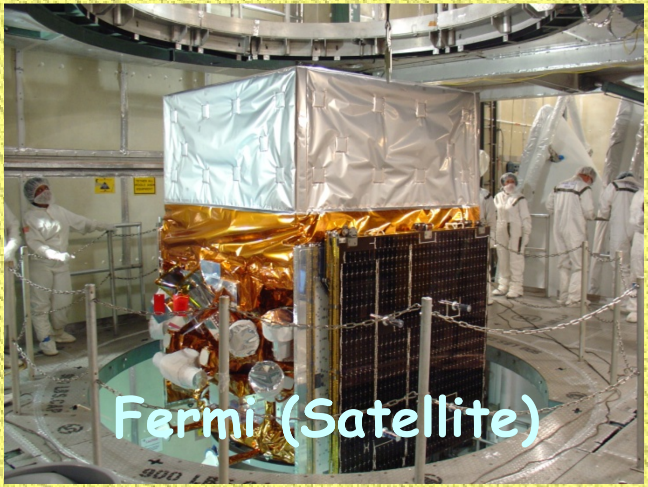


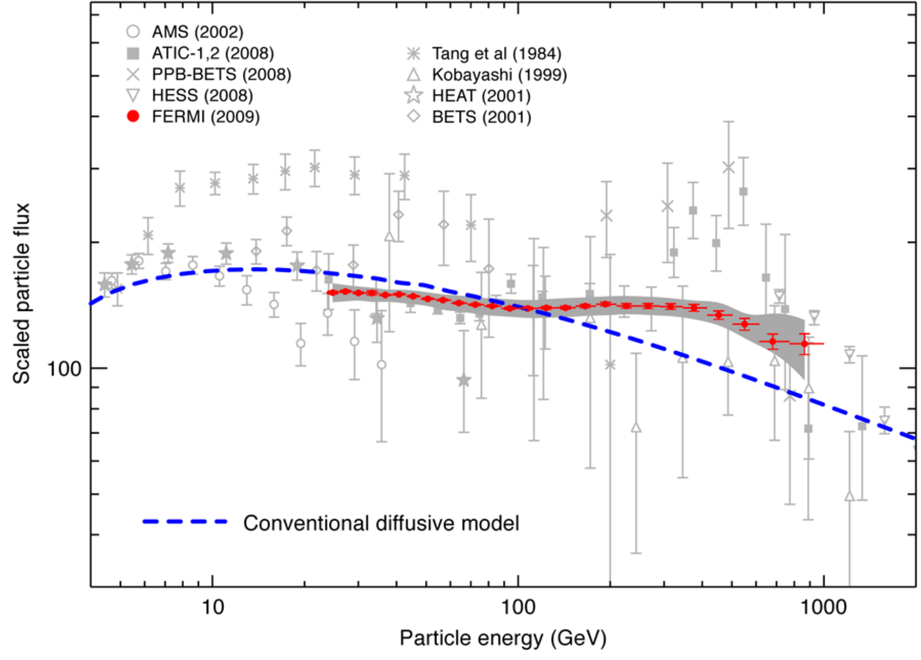
Figure 3 | ATIC results showing agreement with previous data at lower energy and with the imaging calorimeter PPB-BETS at higher energy. Th

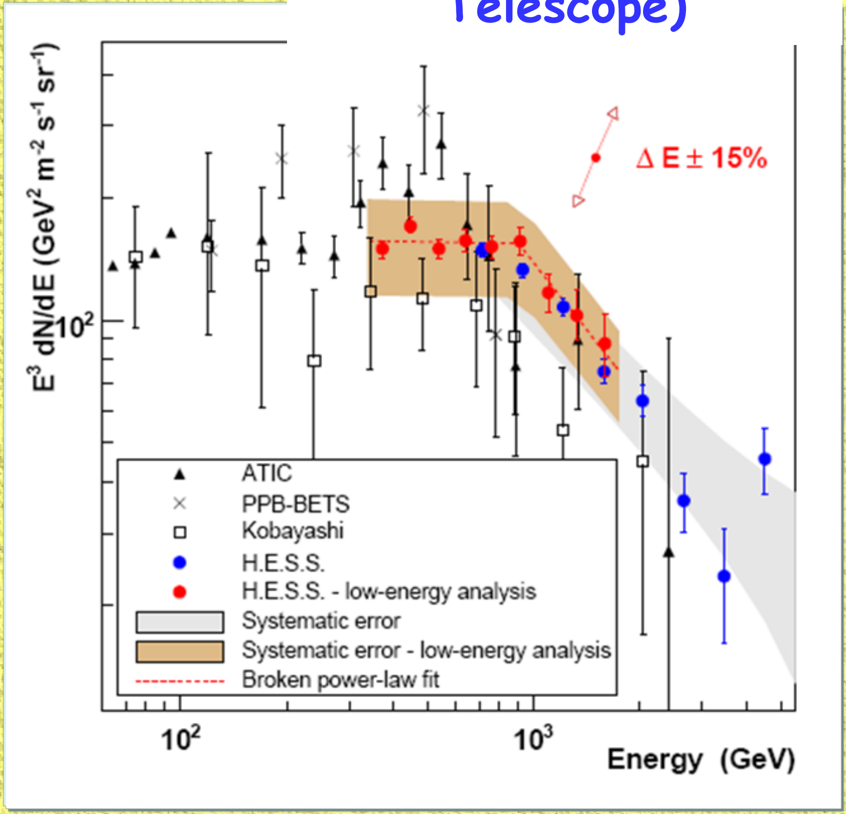
But ! New May 2009 Results …..



Fermi (Satellite)

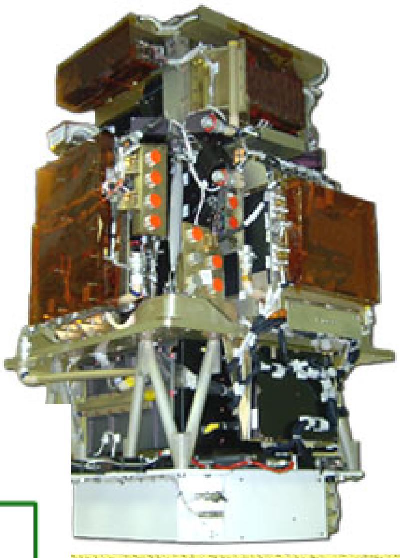
HESS (Air Cerenkov Telescope)

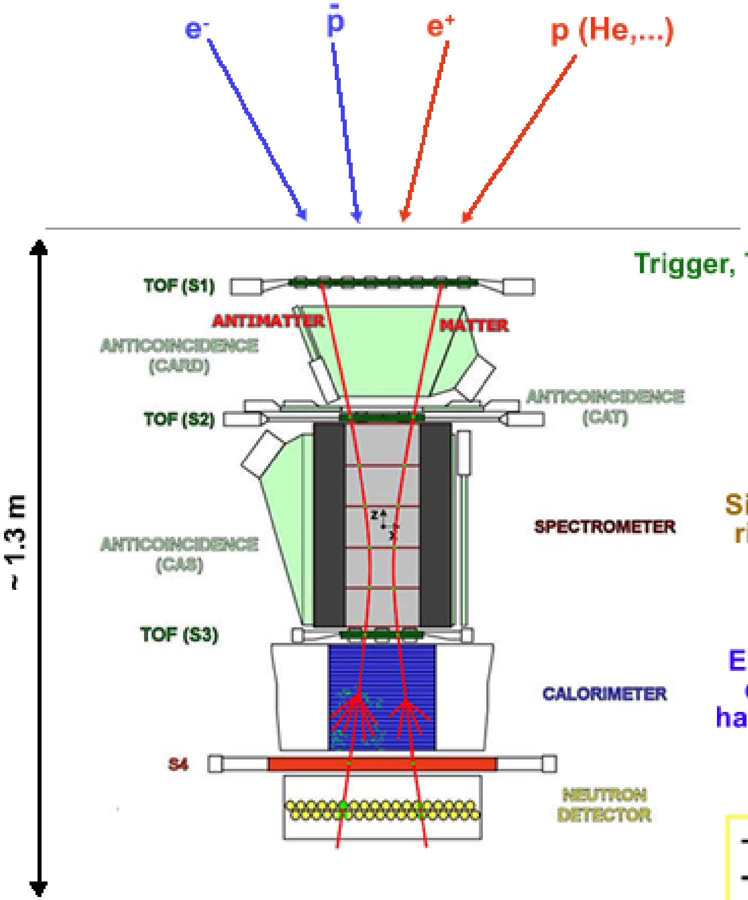




PaMe&La

a Payload for Antimatter Matter Exploration and Light–nuclei Astrophysics





~470 Kg / ~360 W

Trigger, ToF, dE/dx

- S1, S2, S3; double layers, x-y
- plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

Sign of charge, rigidity, dE/dx

- Permanent magnet, 0.43 T
- 21.5 cm^2 sr
- 6 planes double-sided silicon strip detectors (300 µm)
- 3 µm resolution in bending view → MDR ~800 GV (6 plane) ~500 GV (5 plane)

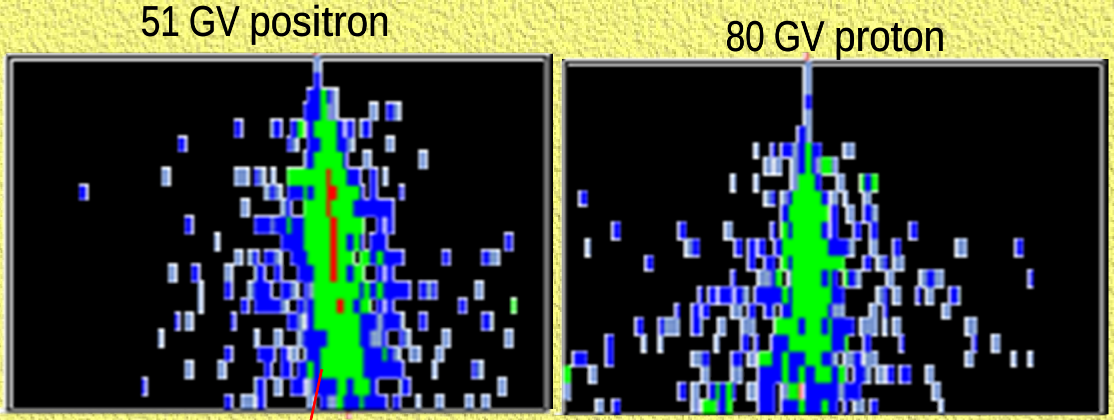
Electron energy, dE/dx, lepton-hadron separation

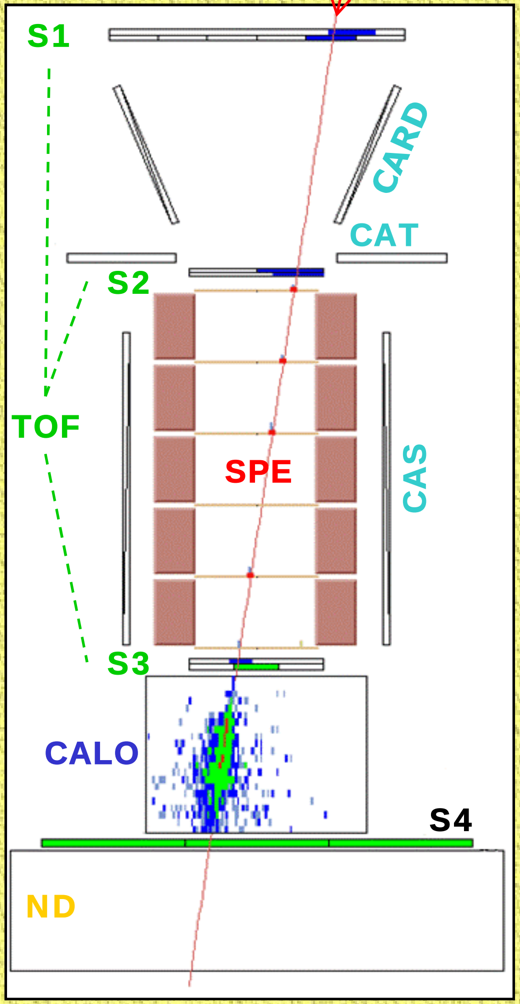
- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm^2 sr

- 36 ^3He counters
- $^3He(n,p)T$; E_p = 780 keV
- 1 cm thick poly + Cd moderator
- 200 µs collection

e/p separation:

- Calo-E-fraction
- Energy-momentum match
- Shower start point
- Shower long./lat profile





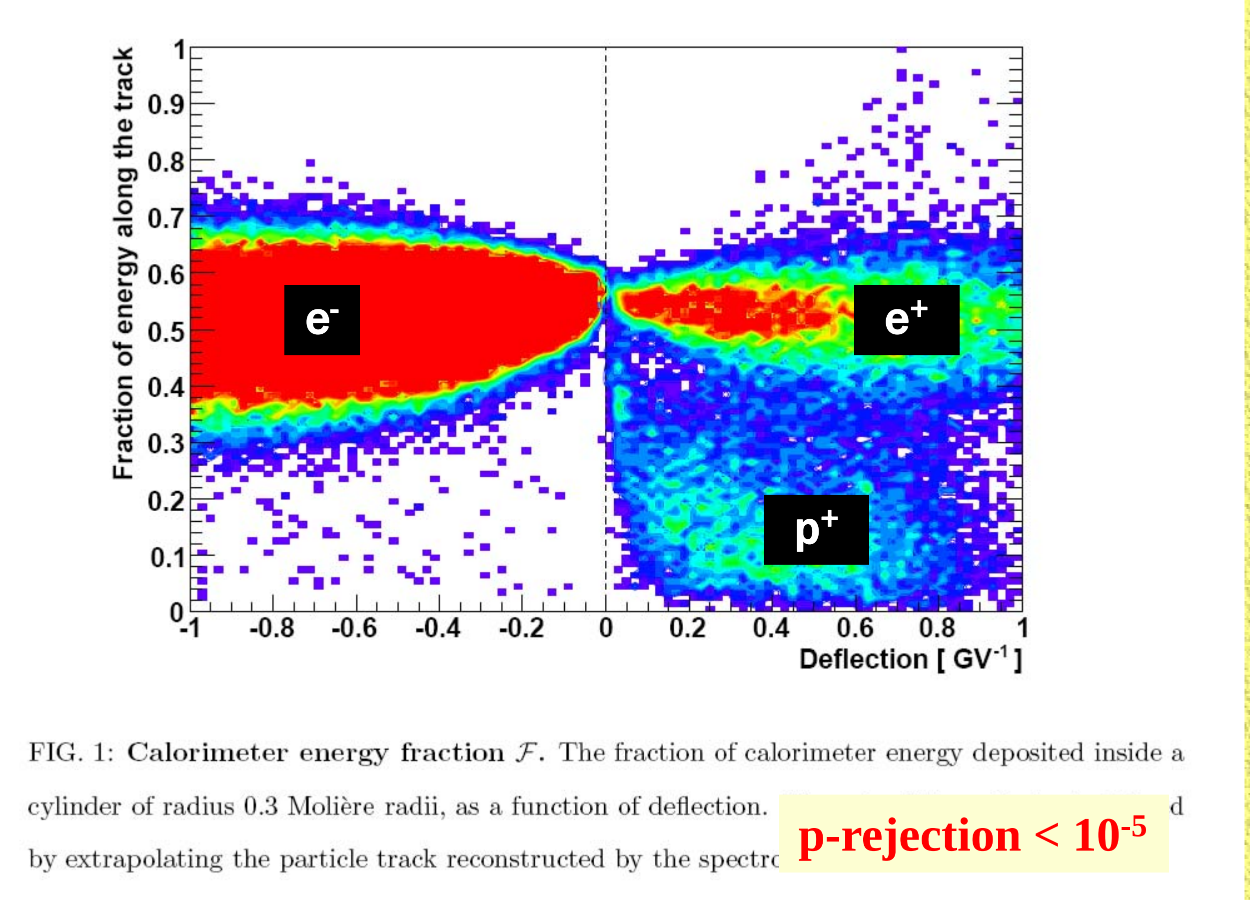


FIG. 1: **Calorimeter energy fraction $\mathcal{F}$.** The fraction of calorimeter energy deposited inside a cylinder of radius 0.3 Molière radii, as a function of deflection. d by extrapolating the particle track reconstructed by the spectr

p-rejection < 10^{-5}

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

O. Adriani[1,2], G. C. Barbarino[3,4], G. A. Bazilevskaya[5], R. Bellotti[6,7], M. Boezio[8], E. A. Bogomolov[9], L. Bonechi[1,2], M. Bongi[2], V. Bonvicini[8], S. Bottai[2], A. Bruno[6,7], F. Cafagna[7], D. Campana[4], P. Carlson[10], M. Casolino[11], G. Castellini[12], M. P. De Pascale[11,13], G. De Rosa[4], N. De Simone[11,13], V. Di Felice[11,13], A. M. Galper[14], L. Grishantseva[14], P. Hofverberg[10], S. V. Koldashov[14], S. Y. Krutkov[9], A. N. Kvashnin[5], A. Leonov[14], V. Malvezzi[11], L. Marcelli[11], W. Menn[15], V. V. Mikhailov[14], E. Mocchiutti[8], S. Orsi[10,11], G. Osteria[4], P. Papini[2], M. Pearce[16], P. Picozza[11,13], M. Ricci[17], S. B. Ricciarini[2], M. Simon[15], R. Sparvoli[11,13], P. Spillantini[1,2], Y. I. Stozhkov[5], A. Vacchi[8], E. Vannuccini[2], G. Vasilyev[9], S. A. Voronov[14], Y. T. Yurkin[14], G. Zampa[8], N. Zampa[8] & V. G. Zverev[14]

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Antiparticles account for a small fraction of cosmic rays and are known to be produced in interactions between cosmic-ray nuclei and atoms in the interstellar medium[1], which is referred to as a 'secondary source'. Positrons might also originate in objects such as pulsars[2] and microquasars[3] or through dark matter annihilation[4], which would be 'primary sources'. Previous statistically limited measurements[5–7] of the ratio of positron and electron fluxes have been interpreted as evidence for a primary source for the positrons, as has an increase in the total electron+positron flux at energies between 300 and 600 GeV (ref. 8). Here we report a measurement of the positron fraction in the energy range 1.5–100 GeV. We find that the positron fraction increases sharply over much of that range, in a way that appears to be completely inconsistent with secondary sources. We therefore conclude that a primary source, be it an astrophysical object or dark matter annihilation, is necessary.

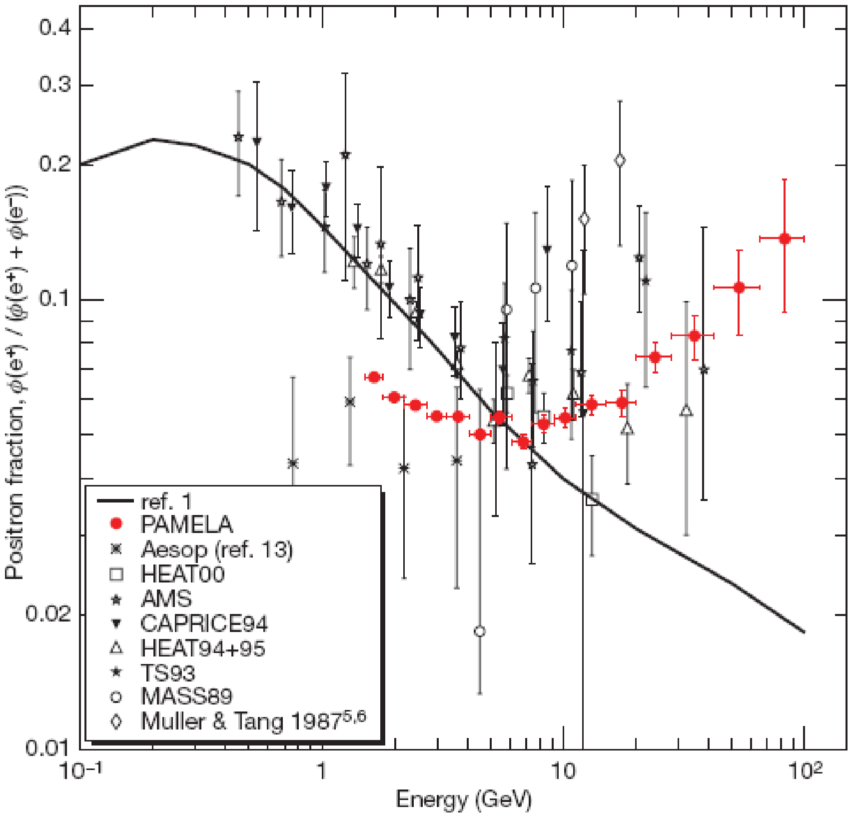
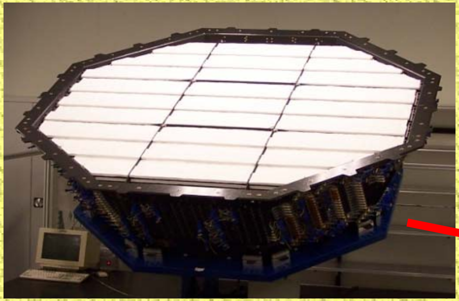


Figure 2 | PAMELA positron fraction with other experimental data and with secondary production model. The positron fraction measured by the

AMS: Construction of the detectors is complete.
Expected Launch : Fall 2010

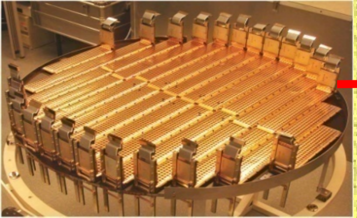
TRD

e



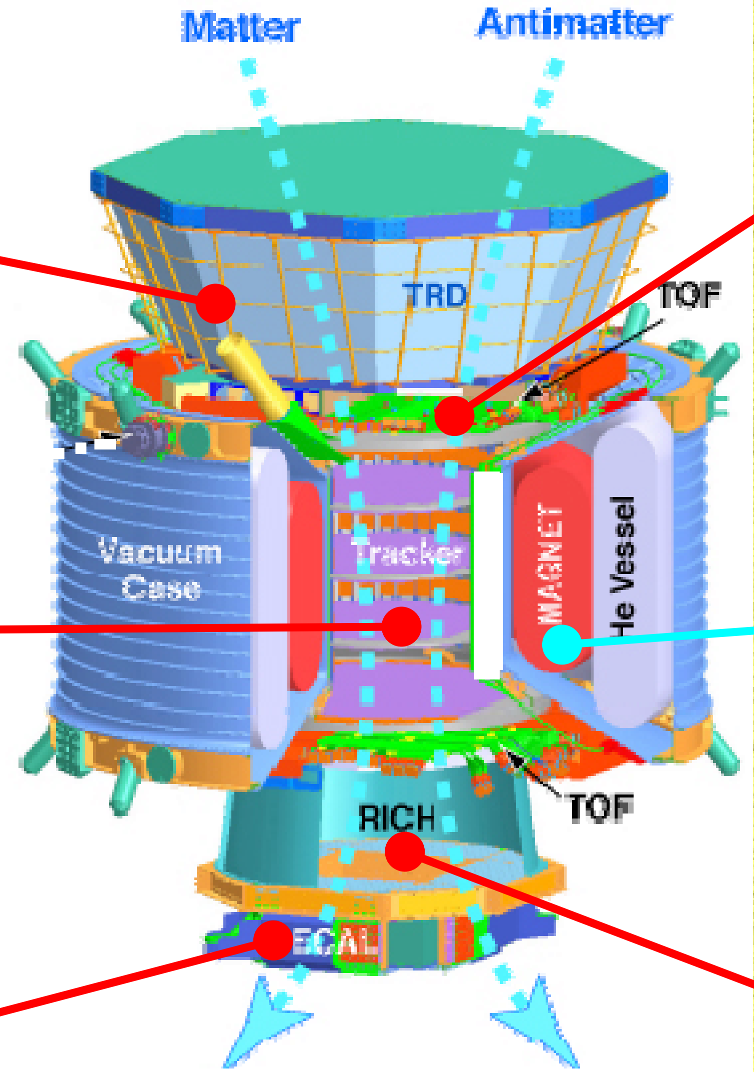
Silicon Tracker

Z, P



Calorimeter

e, γ



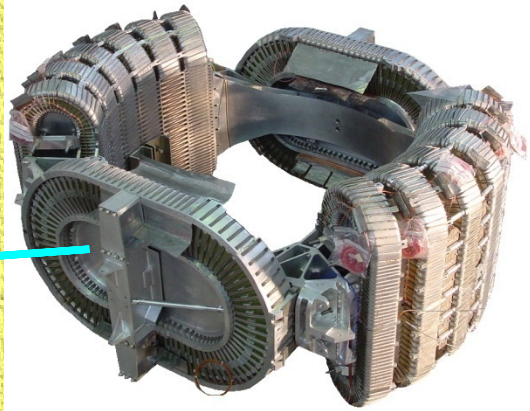
Size: 3m x 3m x 3m
Weight: 7 tons

Time of Flight

v, Z

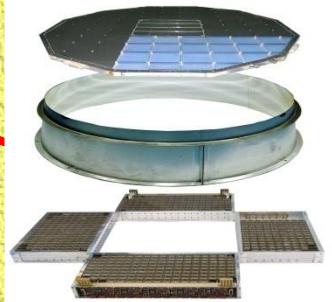
Magnet

P



RICH

v, Z



AMS-2 Sensitivities …

… charge determination till ~500 GeV

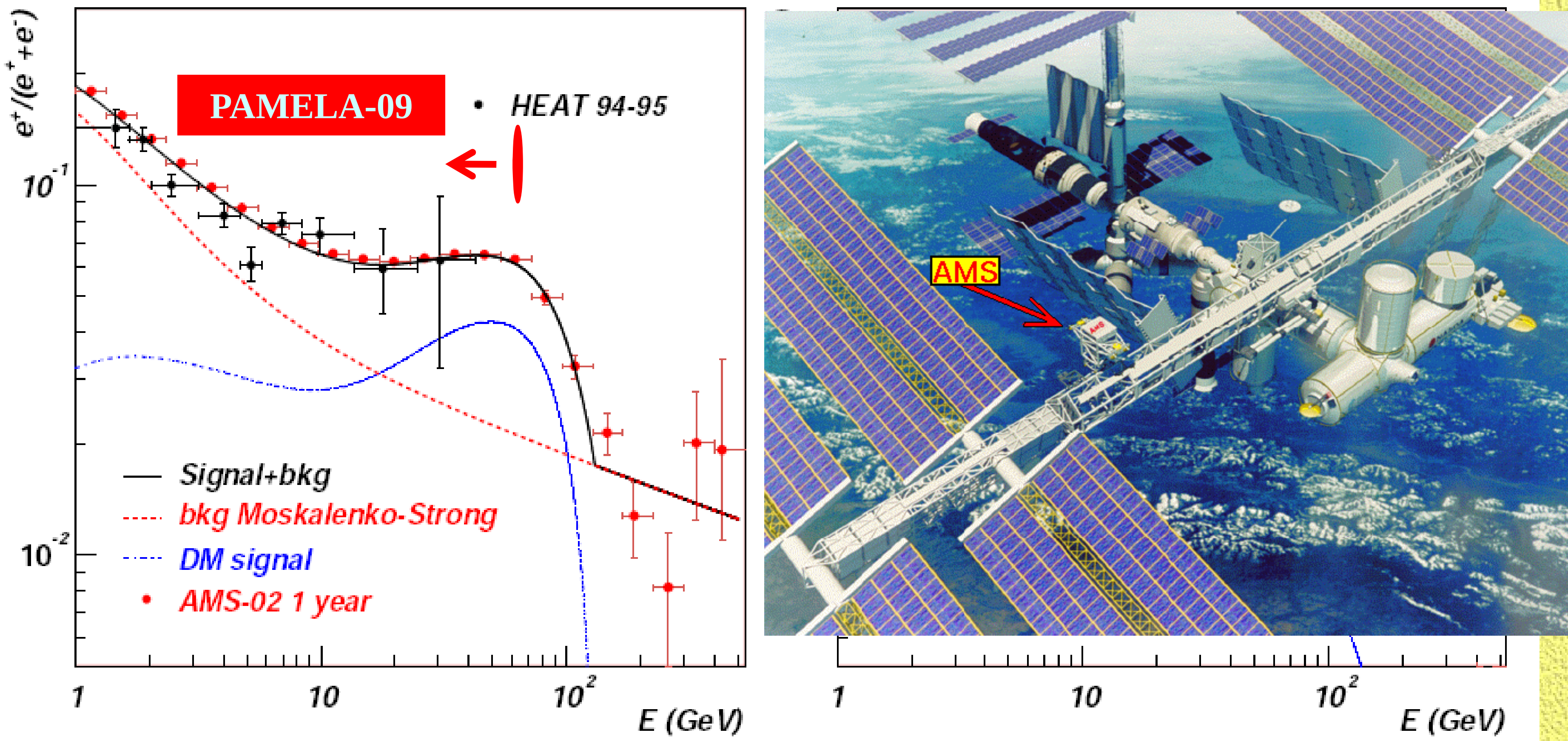
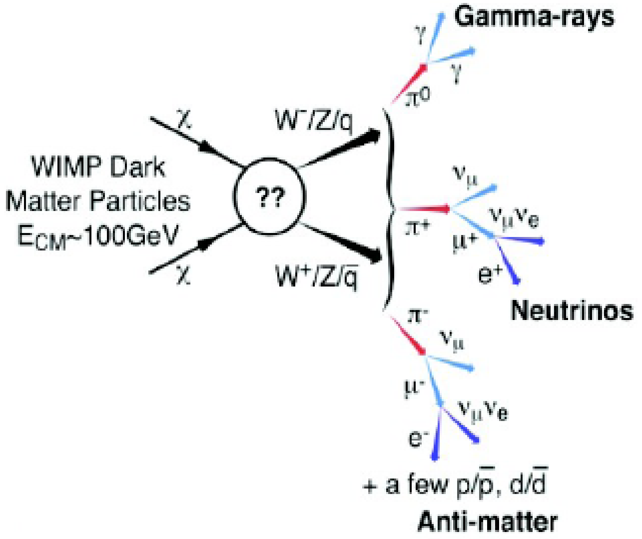


Fig. 1. AMS-02 e^+ fraction in the case of a primary e^+ from annihilating χ [11]

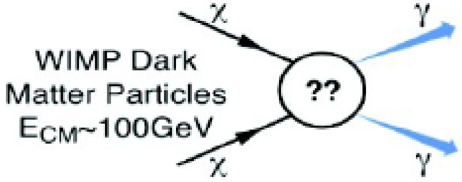
γ-rays from WIMP annihilation

Continuum spectrum with cutoff at M_χ



Spectral line at M_χ

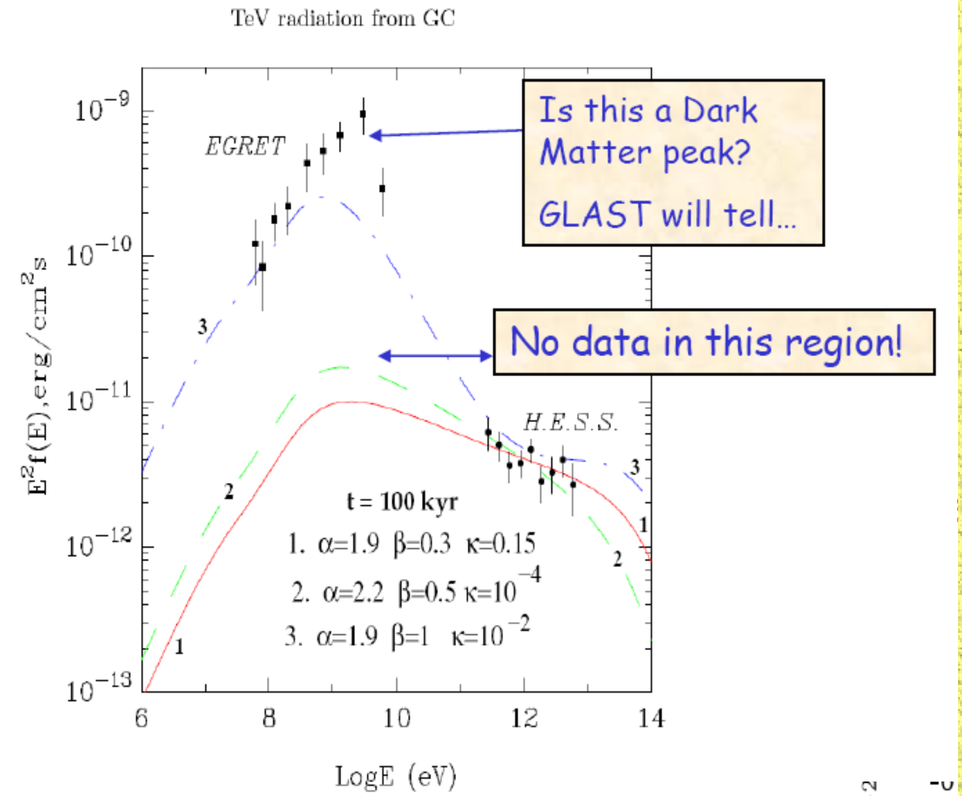
- Detection of prompt annihilation into $\gamma\gamma$ (γZ^0) would provide smoking gun for dark matter annihilation
- Requires best energy resolution
- However, annihilation fraction in the range 10^{-3}-10^{-4} (depending on the model)



Taking Data : GLAST/Fermi

Anomalous Cosmic Gamma Spectrum

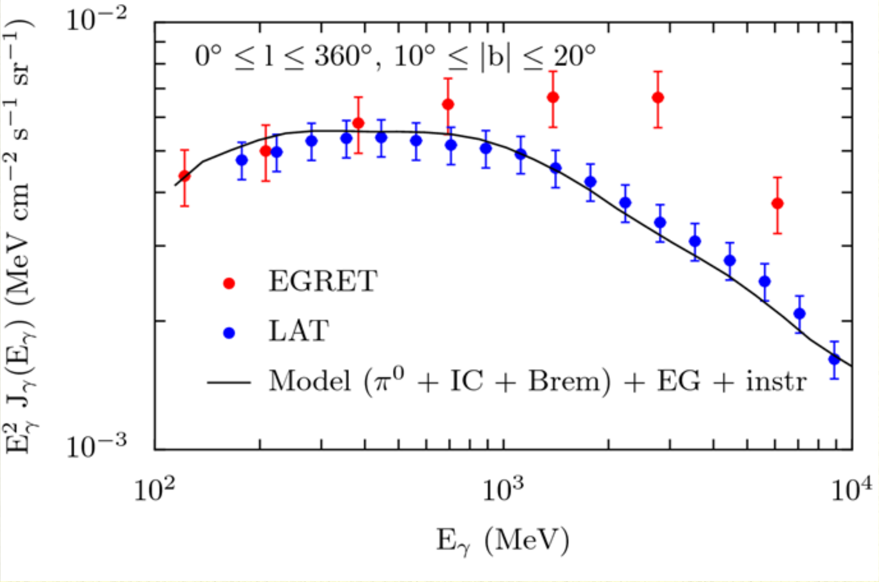
! from ERGET, *NOW* tested by Fermi



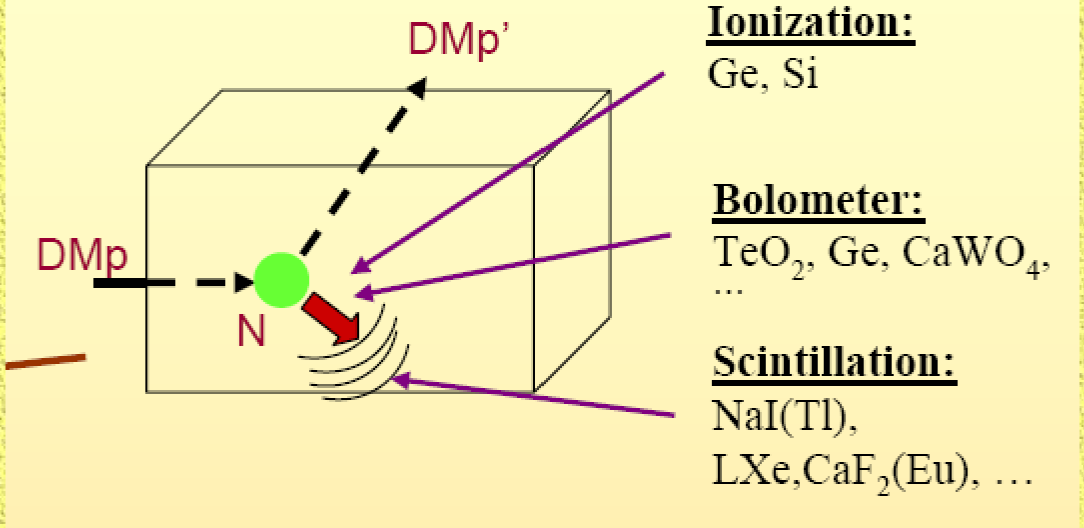
Is this a Dark Matter peak?

GLAST will tell...

No data in this region!



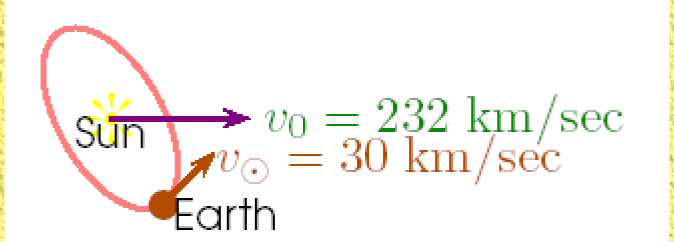
WIMP Direct Detection



Ionization:
Ge, Si

Bolometer:
TeO_2, Ge, $CaWO_4$, …

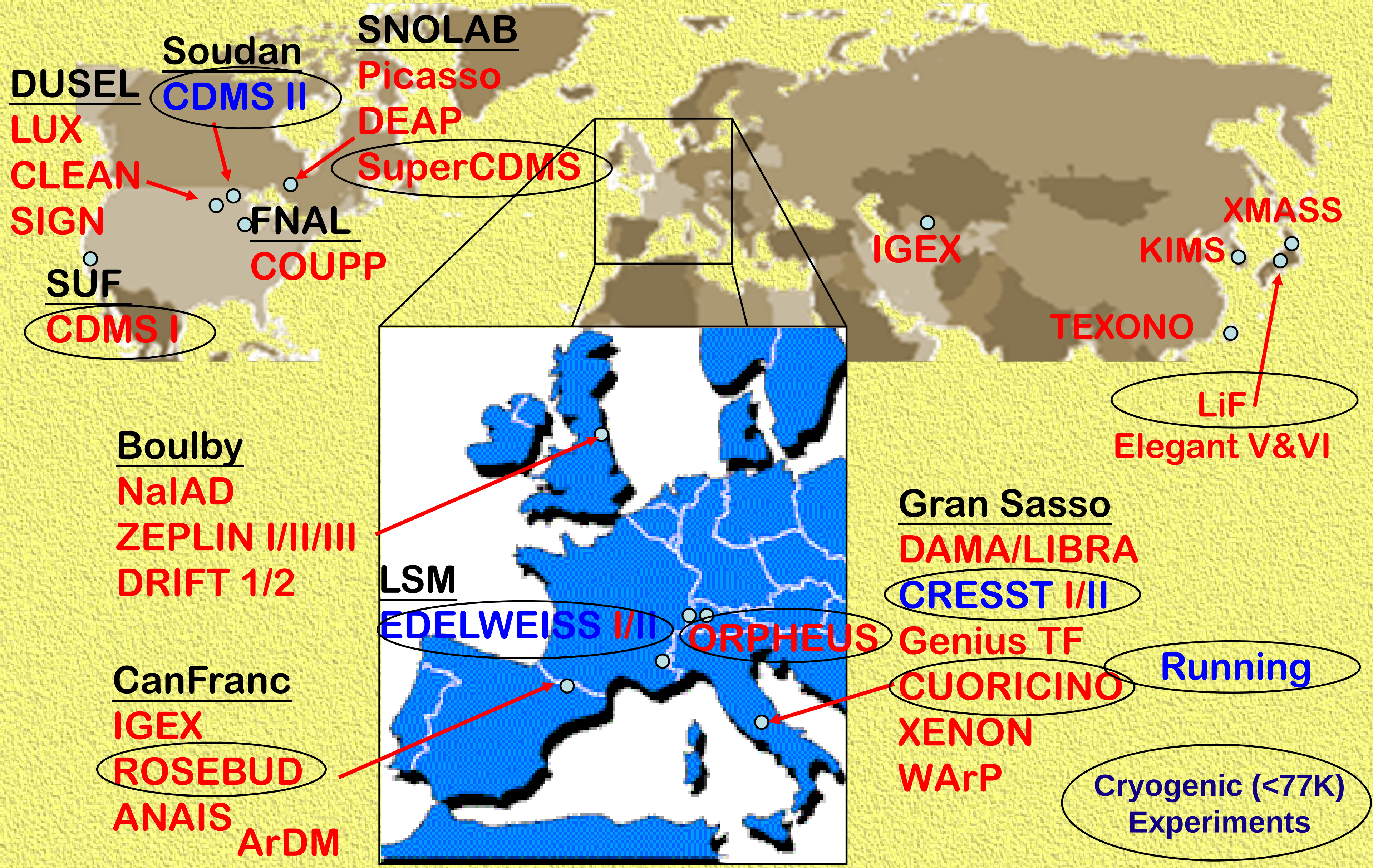
Scintillation:
NaI(Tl),
LXe,CaF_2(Eu), …



- Elastic recoil of non relativistic halo WIMPs off the nuclei
- Both Spin-Independent (~A^2) and Spin-Dependent [~(J+1/J)] Couplings
- Recoil energy of the nucleus in the keV range
- Annual modulation effect due to the rotation of the Earth around the Sun
- Directional Recoils, experimentally challenging

WIMP-detection Experiments Worldwide

(from Subject Review TAUP-07)



DUSEL
LUX
CLEAN
SIGN

Soudan
CDMS II

SNOLAB
Picasso
DEAP
SuperCDMS

FNAL
COUPP

SUF
CDMS I

IGEX

KIMS

XMASS

TEXONO

LiF
Elegant V&VI

Boulby
NaIAD
ZEPLIN I/II/III
DRIFT 1/2

LSM
EDELWEISS I/II

ORPHEUS

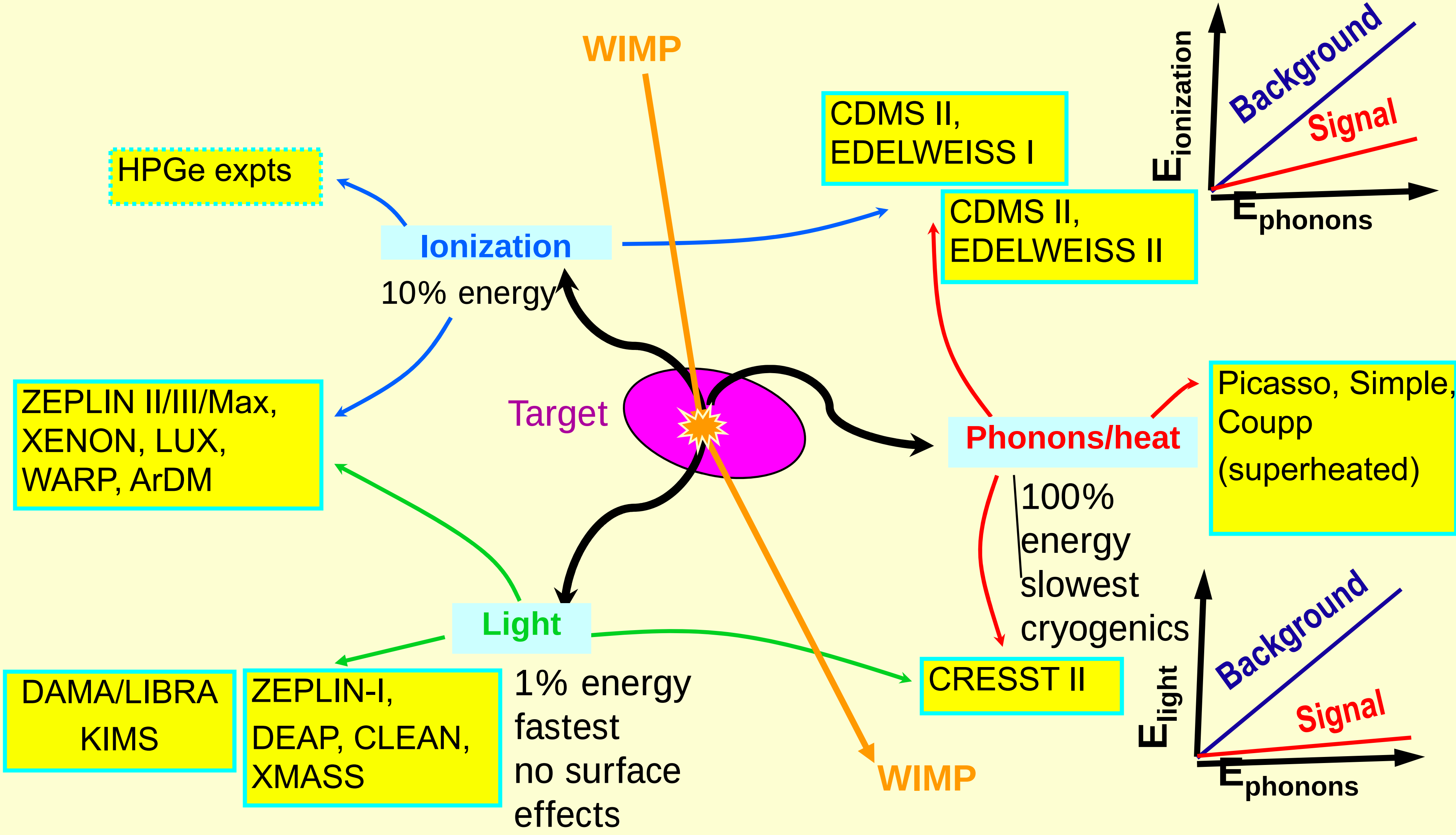
CanFranc
IGEX
ROSEBUD
ANAIS
ArDM

Gran Sasso
DAMA/LIBRA
CRESST I/II
Genius TF
CUORICINO
XENON
WArP

Running

Cryogenic (<77K) Experiments

Detector Techniques - Present Focus : Nuclear Vs Electron recoils



WIMP

Target

WIMP

Ionization

10% energy

HPGe expts

CDMS II,
EDELWEISS I

ZEPLIN II/III/Max,
XENON, LUX,
WARP, ArDM

Phonons/heat

100%
energy
slowest
cryogenics

CDMS II,
EDELWEISS II

Picasso, Simple,
Coupp
(superheated)

CRESST II

Light

1% energy
fastest
no surface
effects

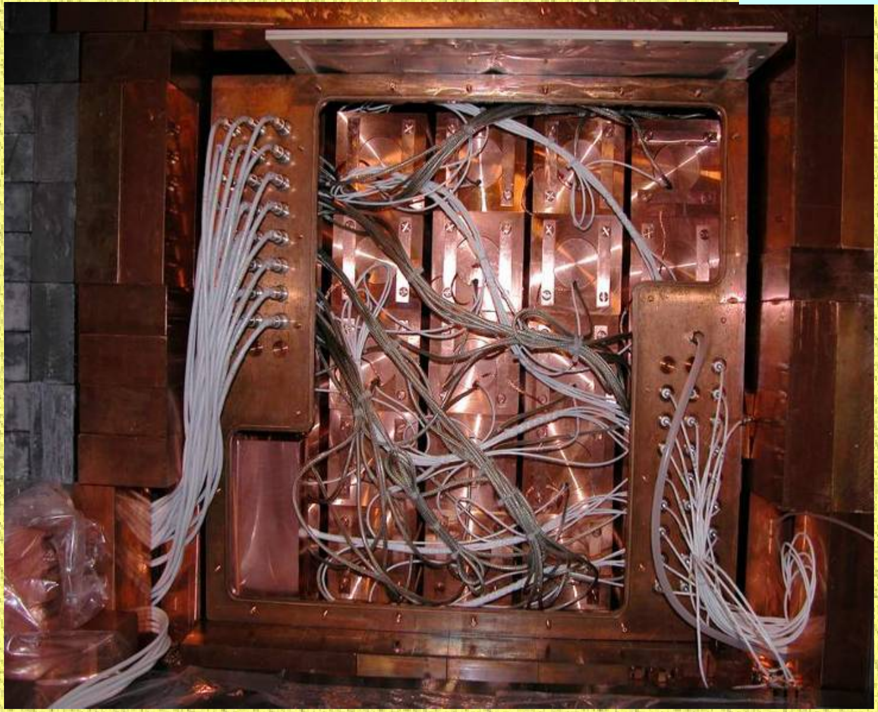
DAMA/LIBRA
KIMS

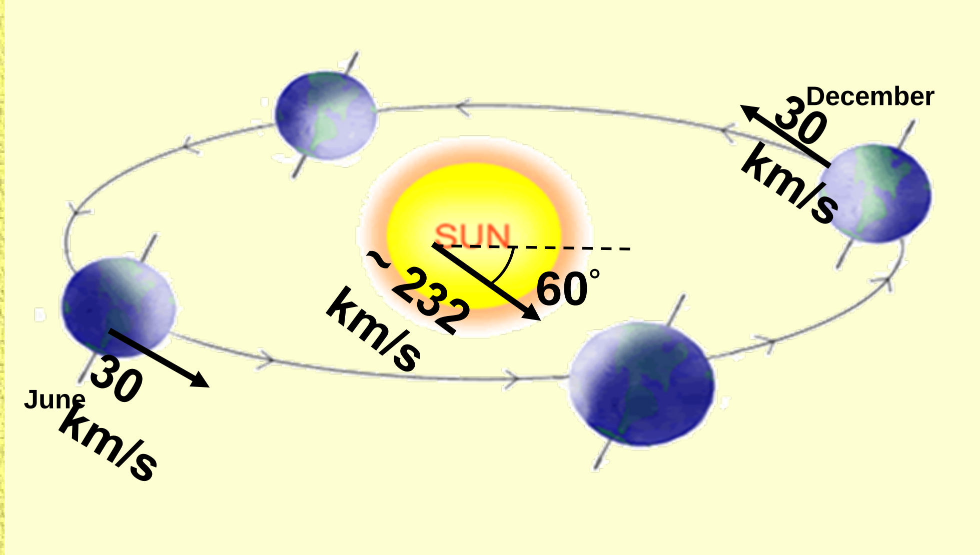
ZEPLIN-I,
DEAP, CLEAN,
XMASS

◎ **Future : Lower Threshold ; Direction Sensitive**

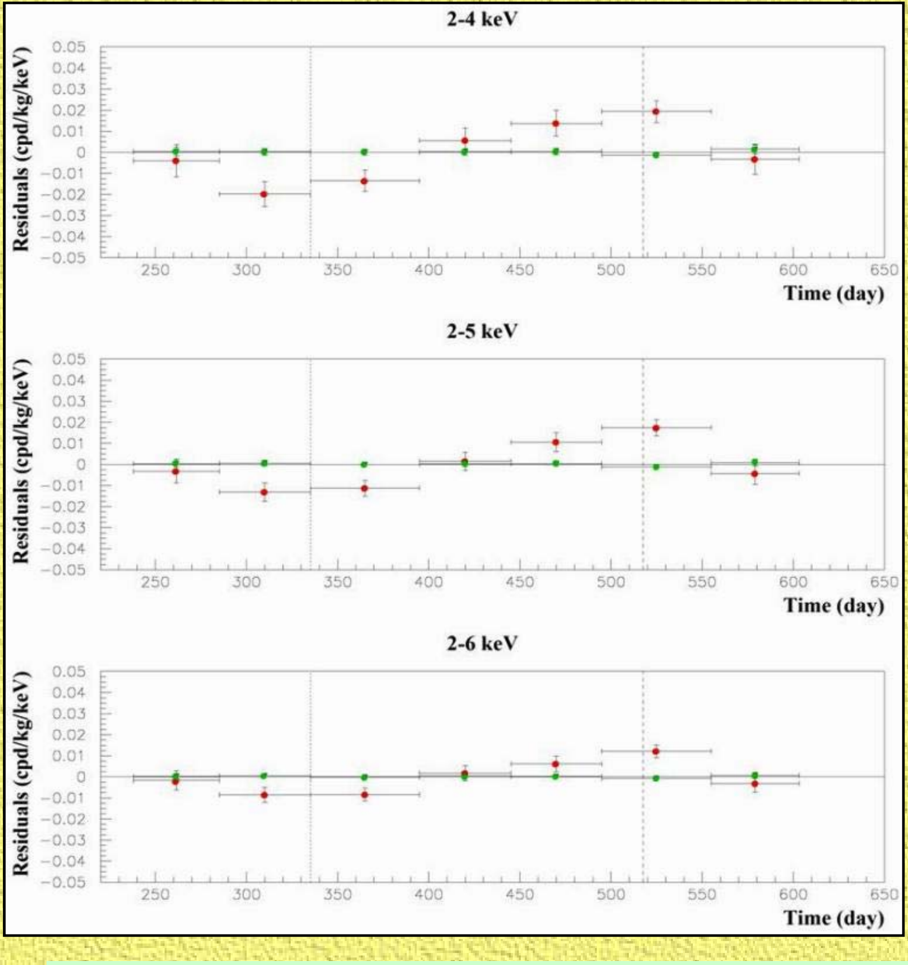
DAMA/LIBRA

- NaI(Tl) Scintillator at Gran Sasso : total 0.82 ton-year data
- Observe annual modulation in the 2-6 keV single-hit signal band, total 11 cycles, > 8σ
- No modulations at higher energy & for multiple-hits

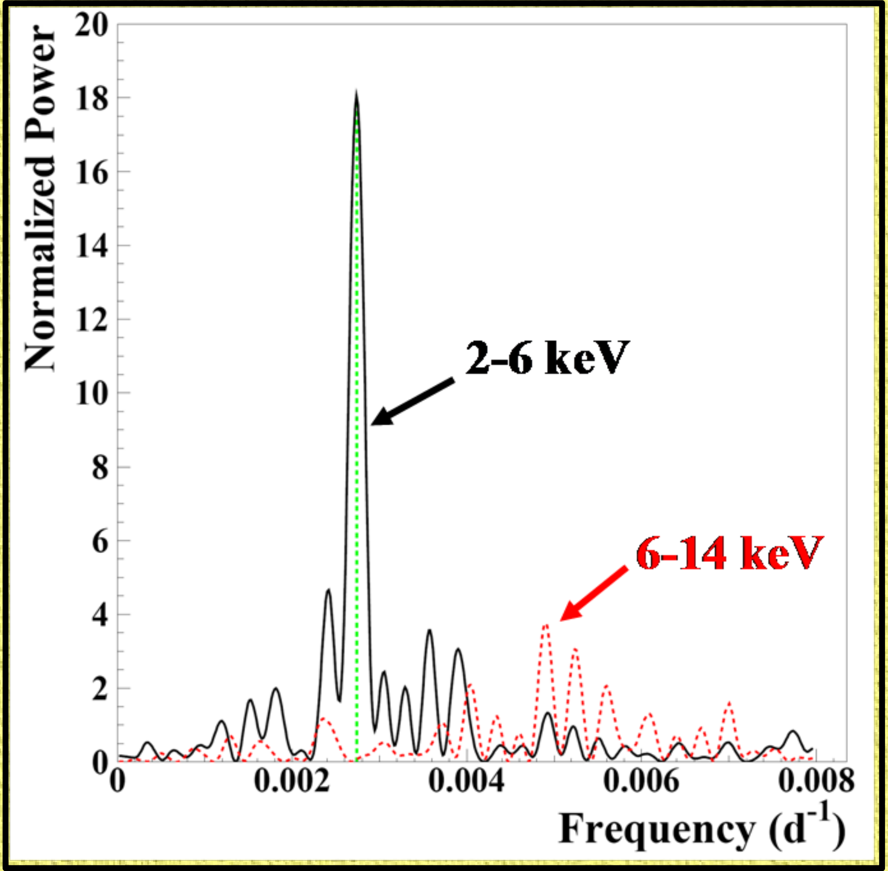




- *multiple-hits* residual rate (green points) vs single-hit residual rate (red points)



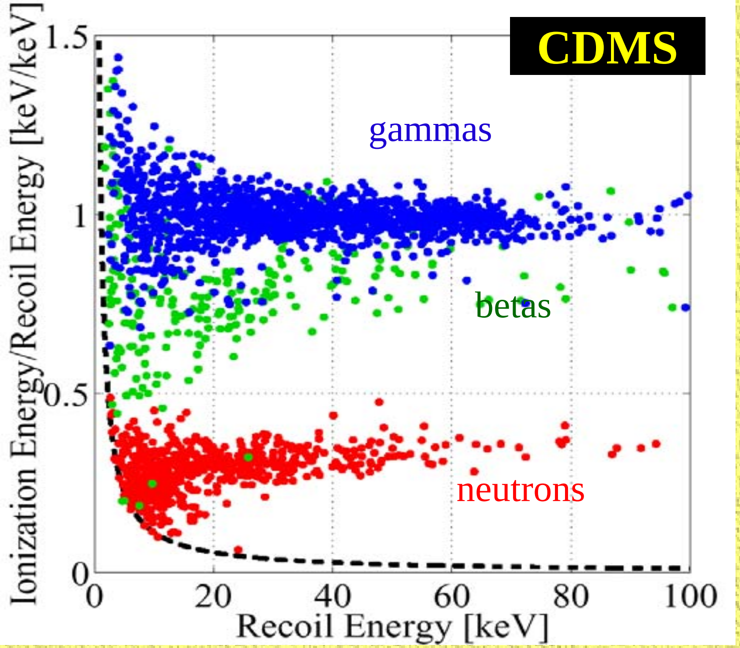
Single-Hit Power Spectrum

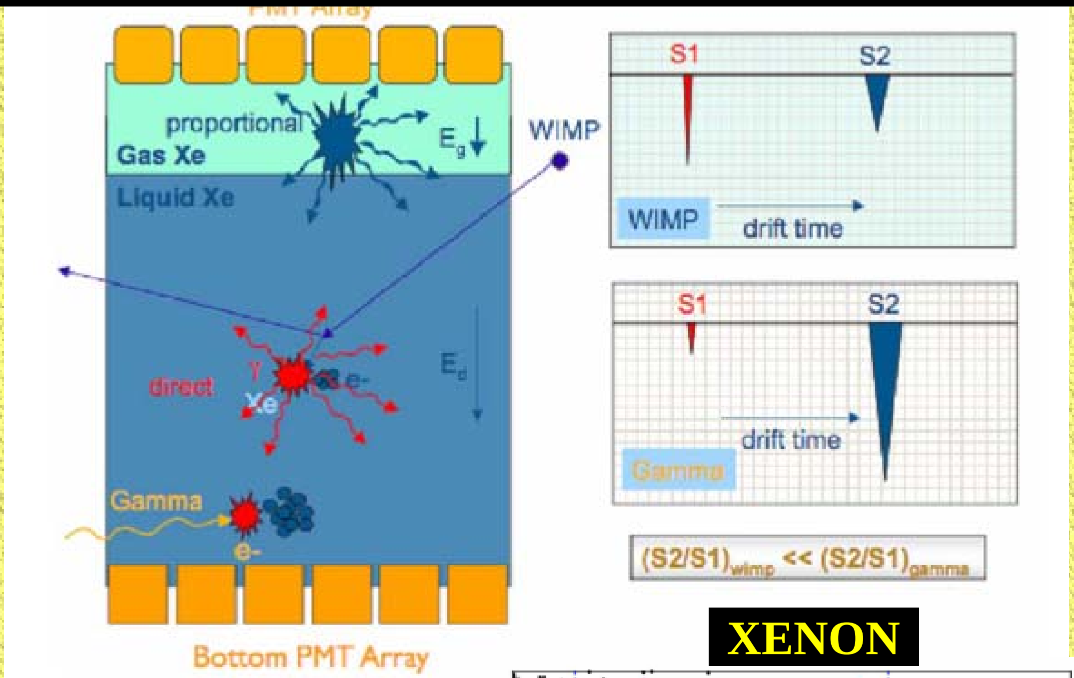


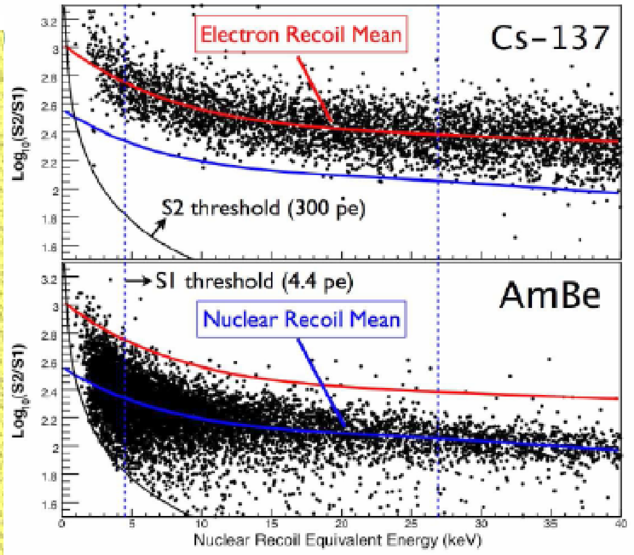
- **No Modulation for multiple hits at 2-6 keV**
- **No Modulation for single hit above 6 keV**

Sensitive Techniques: Phonon+Ionization & Dual Phase Xenon

⇨ Nuclear Vs electron recoils differentiation





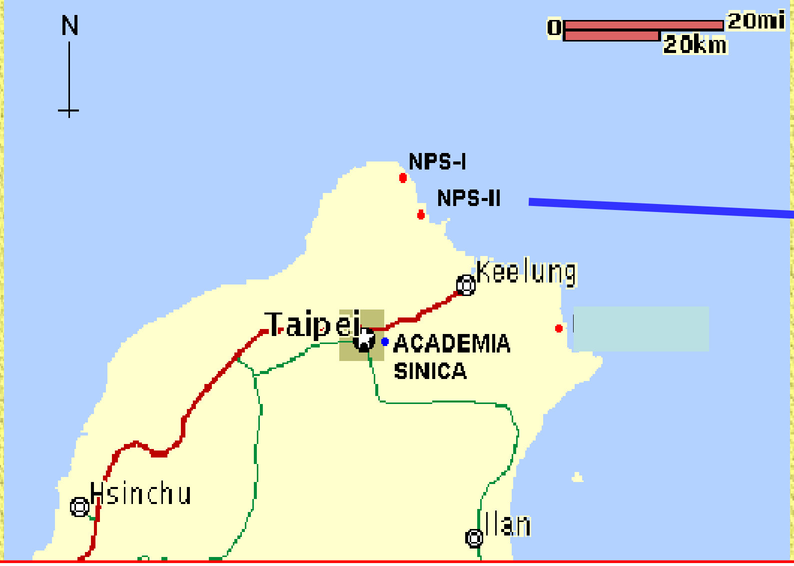


TEXONO Collaboration

Collaboration : **Taiwan** (AS, INER, KSNPS, NTU) ; **China** (IHEP, CIAE, THU, NKU) ; **Turkey** (METU) ; **India** (BHU)

Program: **Low Energy Neutrino & Astroparticle Physics**

Kuo Sheng（國 聖） *Power Reactor* :

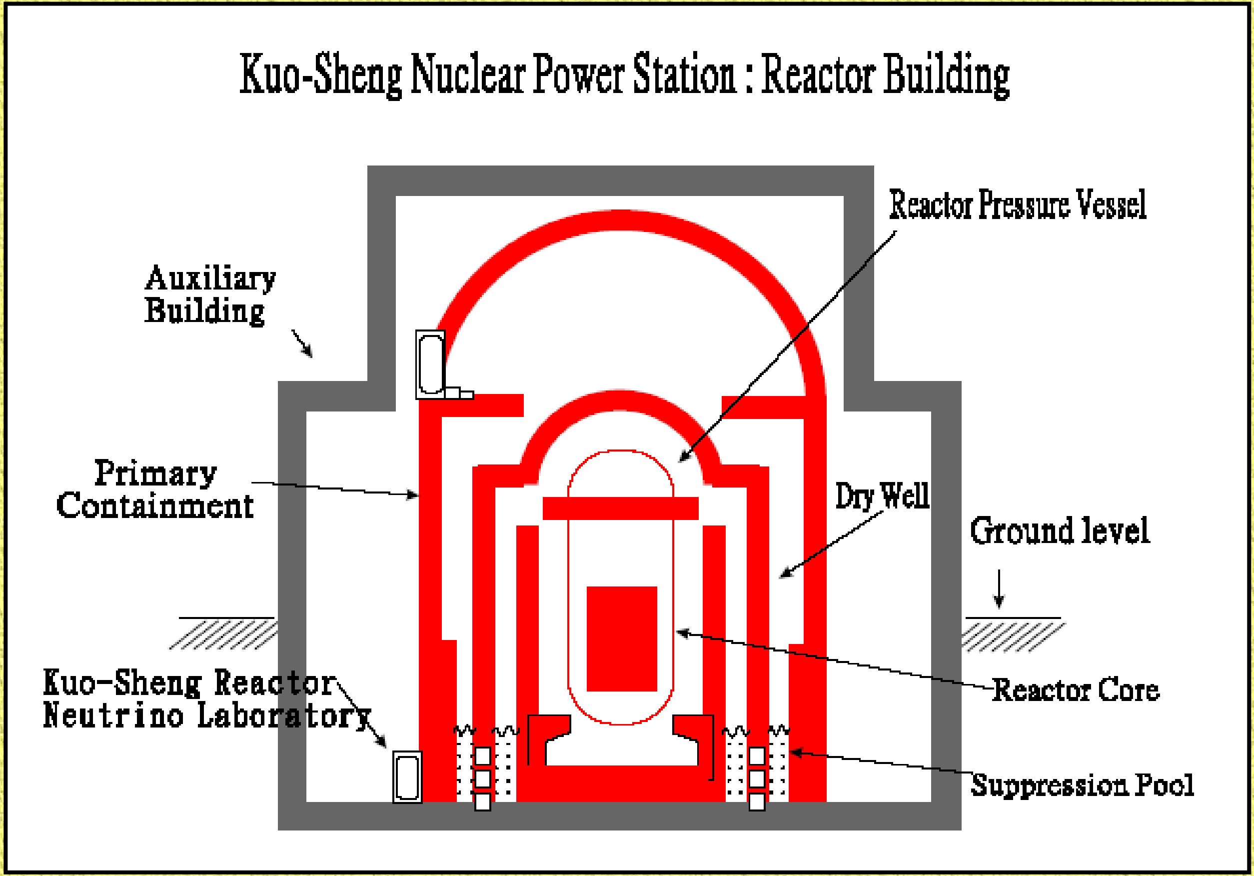


KS NPS-II ： 2 cores × 2.9 GW

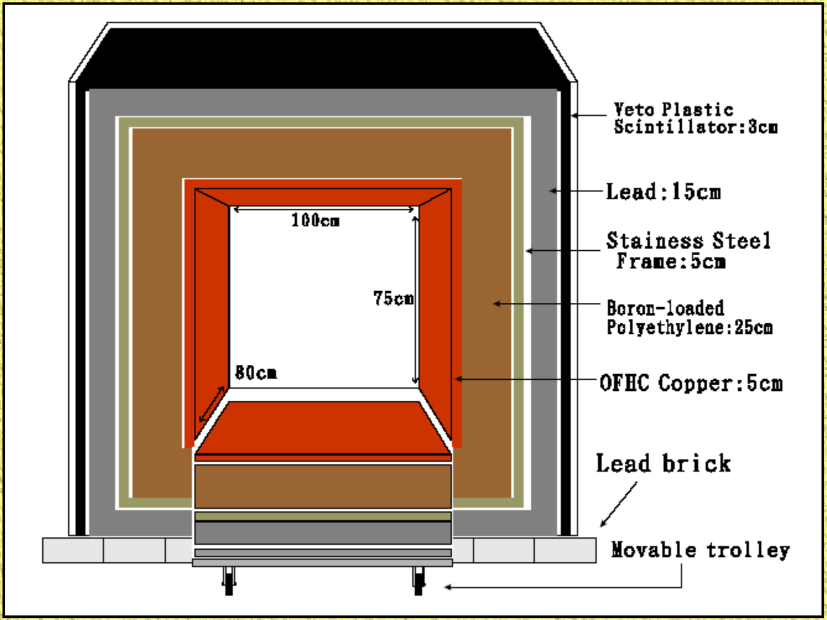
Powerful collaboration. Scientists from Taiwan and mainland China are studying neutrino emissions from this nuclear power plant outside Taipei.

Kuo Sheng Reactor Neutrino Laboratory

Front Gate


Kuo-Sheng Nuclear Power Station : Reactor Building

- 28 m from core#1 @ 2.9 GW
- Shallow depth : ~30 meter-water-equivalent
- Reactor Cycle : ~50 days OFF every 18 months



Front View *(cosmic vetos, shieldings, control room …..)*

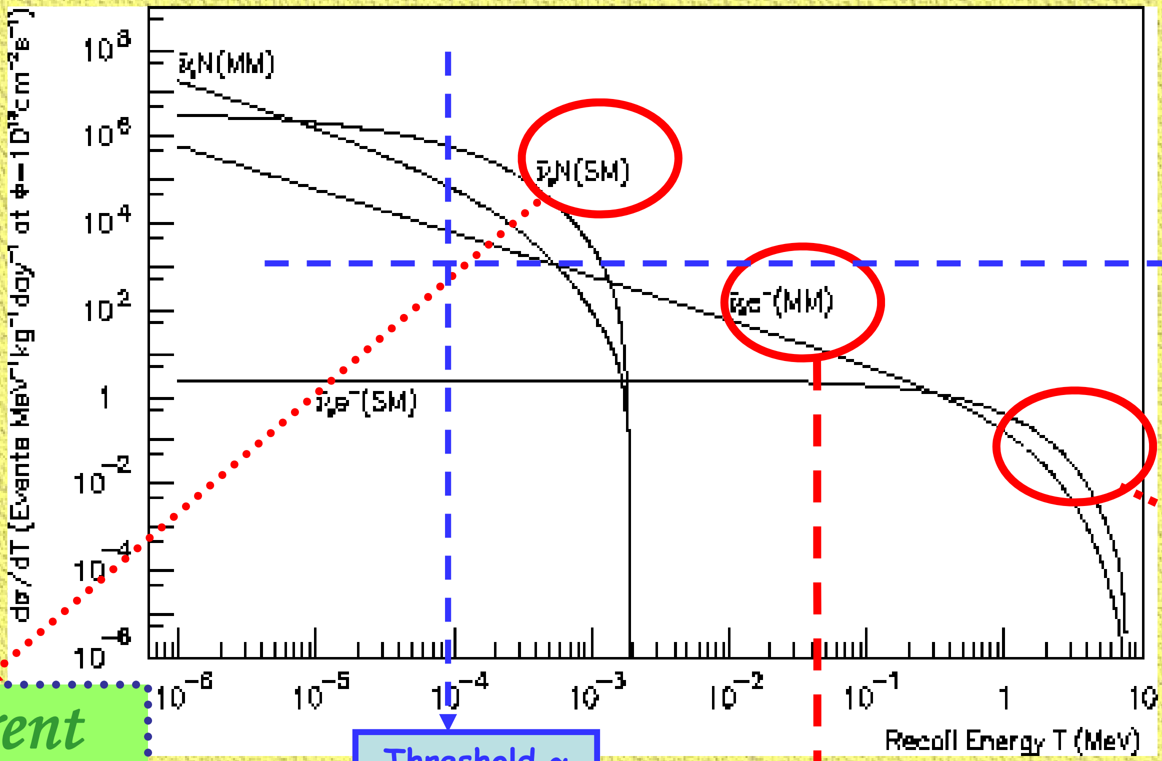
Inner Target Volume

Configuration: Modest yet Unique

Flexible Design: Allows different detectors conf. for different physics

Neutrino Properties & Interactions at Reactor

quality ← **Detector requirements** → **mass**



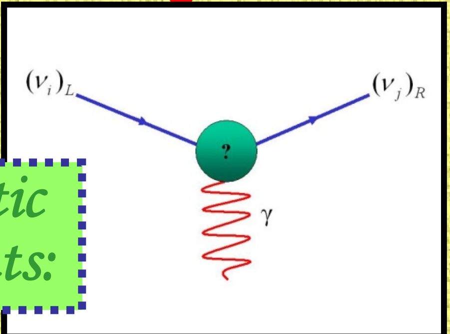
1 counts / kg-keV-day

νN Coherent Scattering

Threshold ~ 100 eV

Standard Model νe Scattering

Magnetic Moments:



PHYSICAL REVIEW D 79, 061101(R) (2009)

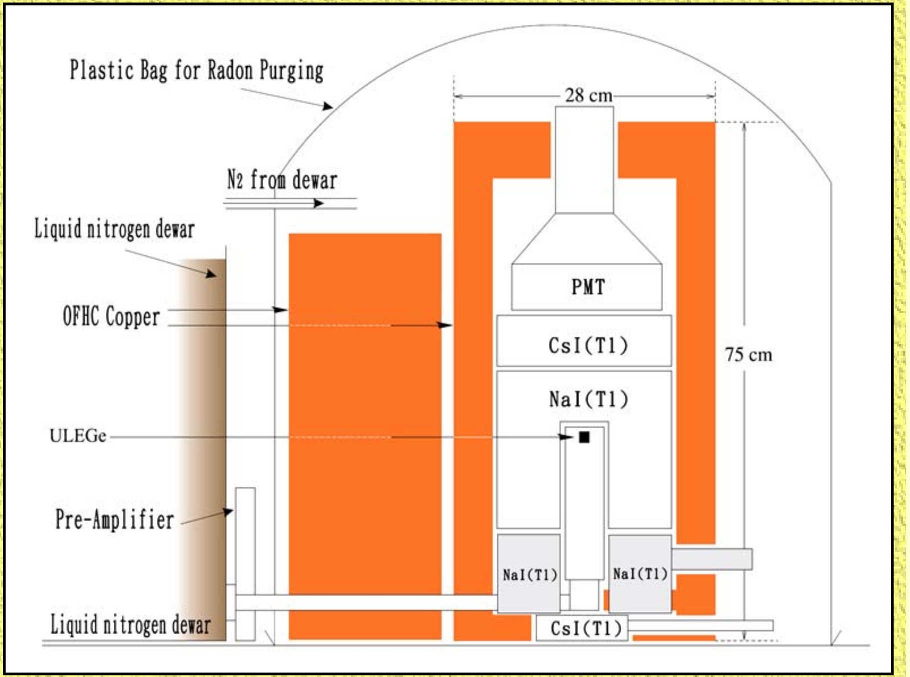
New limits on spin-independent and spin-dependent couplings of low-mass WIMP dark matter with a germanium detector at a threshold of 220 eV

S. T. Lin,[1] H. B. Li,[1] X. Li,[2] S. K. Lin,[1] H. T. Wong,[1,*] M. Deniz,[1,3] B. B. Fang,[2] D. He,[2] J. Li,[2,4] C. W. Lin,[1] F. K. Lin,[1]
X. C. Ruan,[5] V. Singh,[1,6] A. K. Soma,[1,6] J. J. Wang,[1] Y. R. Wang,[1] S. C. Wu,[1] Q. Yue,[2] and Z. Y. Zhou[5]

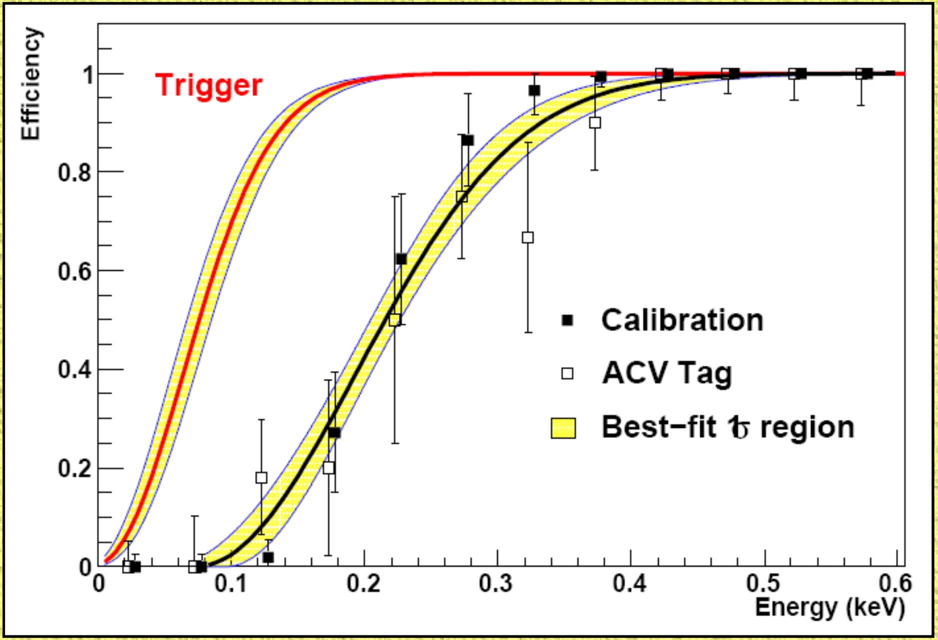
(TEXONO Collaboration)

[1]*Institute of Physics, Academia Sinica, Taipei 115, Taiwan*
[2]*Department of Engineering Physics, Tsinghua University, Beijing 100084, China*
[3]*Department of Physics, Middle East Technical University, Ankara 06531, Turkey*
[4]*Institute of High Energy Physics, Chinese Academy of Science, Beijing 100039, China*
[5]*Department of Nuclear Physics, Institute of Atomic Energy, Beijing 102413, China*
[6]*Department of Physics, Banaras Hindu University, Varanasi 221005, India*
(Received 10 December 2007; revised manuscript received 22 May 2008; published 12 March 2009)

4X5g ULEGe



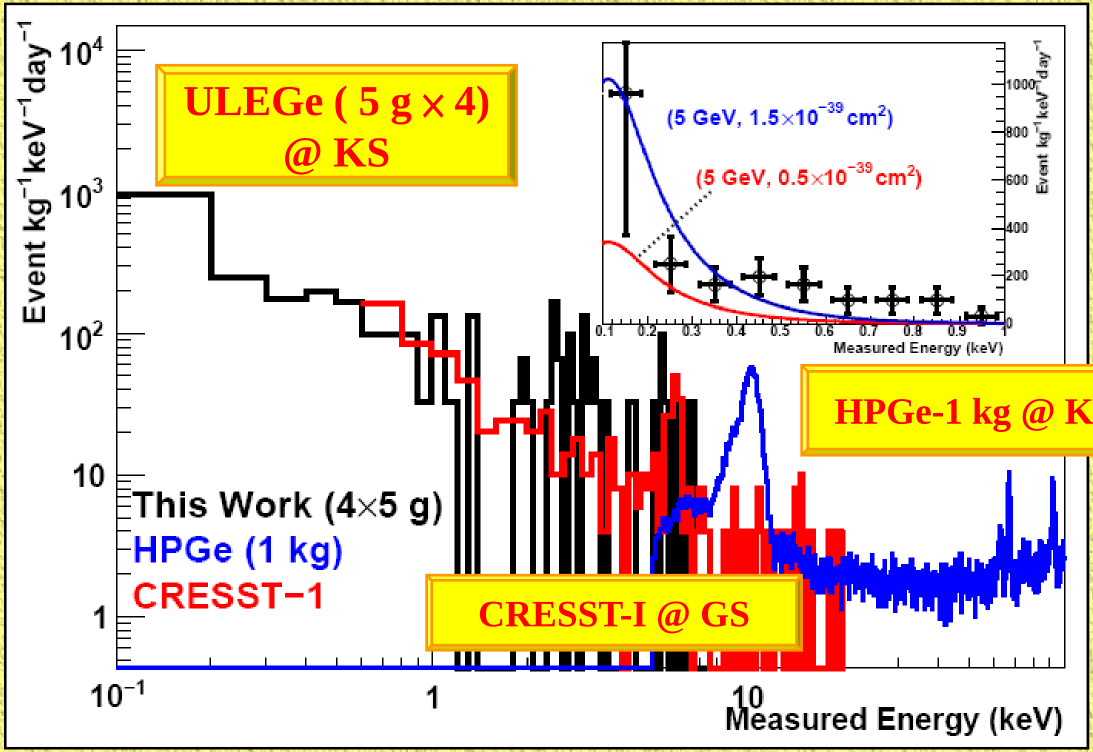
- ***Candidate Events*: selected by Anti-Compton *[ACV : γ]* and Cosmic-Ray *[CRV: μ]* vetos & Pulse-Shape Discrimination *[PSD: electronic noise]***
- ***Critical Issues*: Signal efficiencies for trigger, DAQ & Selection**
- ***Non-Ge Efficiency [DAQ,ACV,CRV]* : evaluated by Random Trigger events.**



Efficiency

ε=50% @ 220 eV

Background comparable to those of Underground Experiments

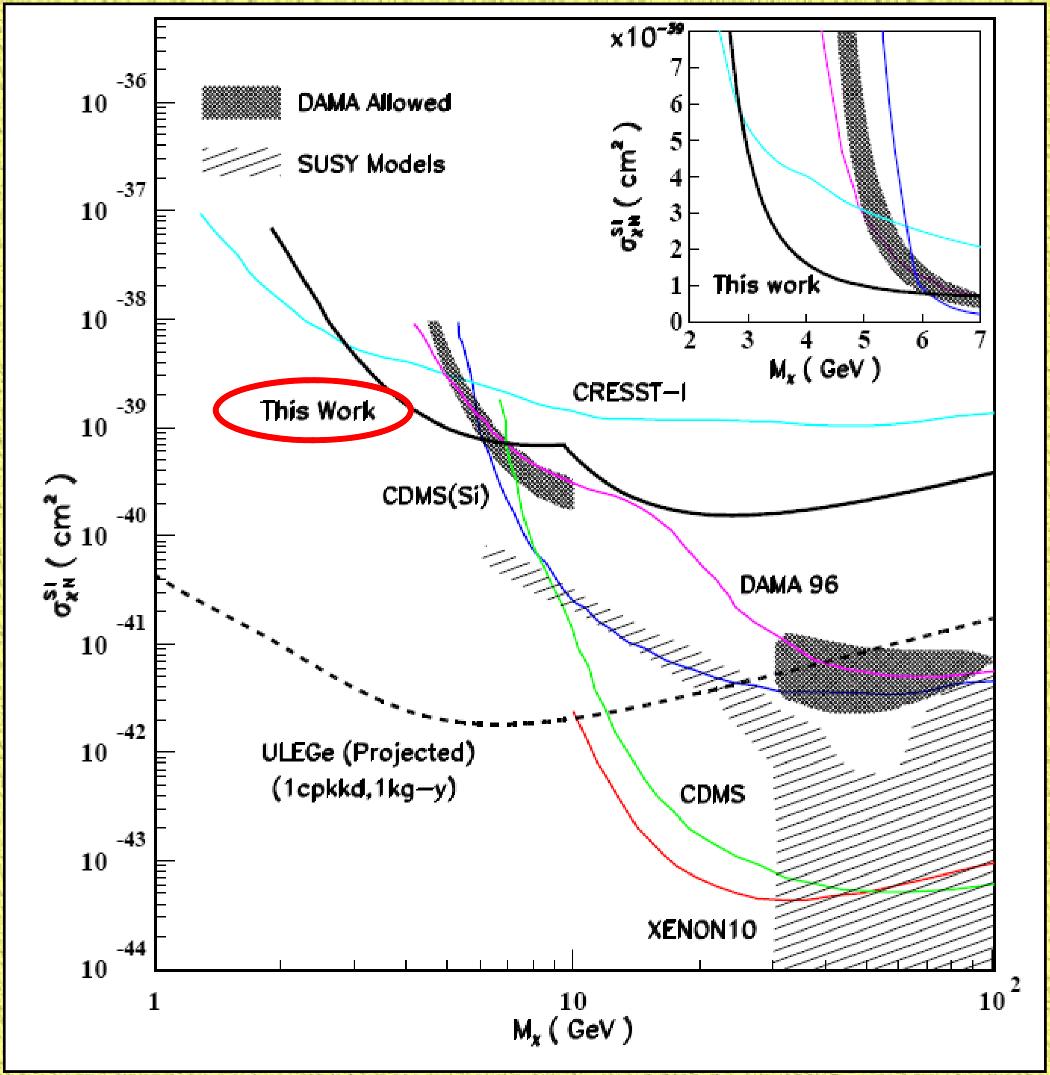


ULEGe (5 g × 4) @ KS

HPGe-1 kg @ KS

CRESST-I @ GS

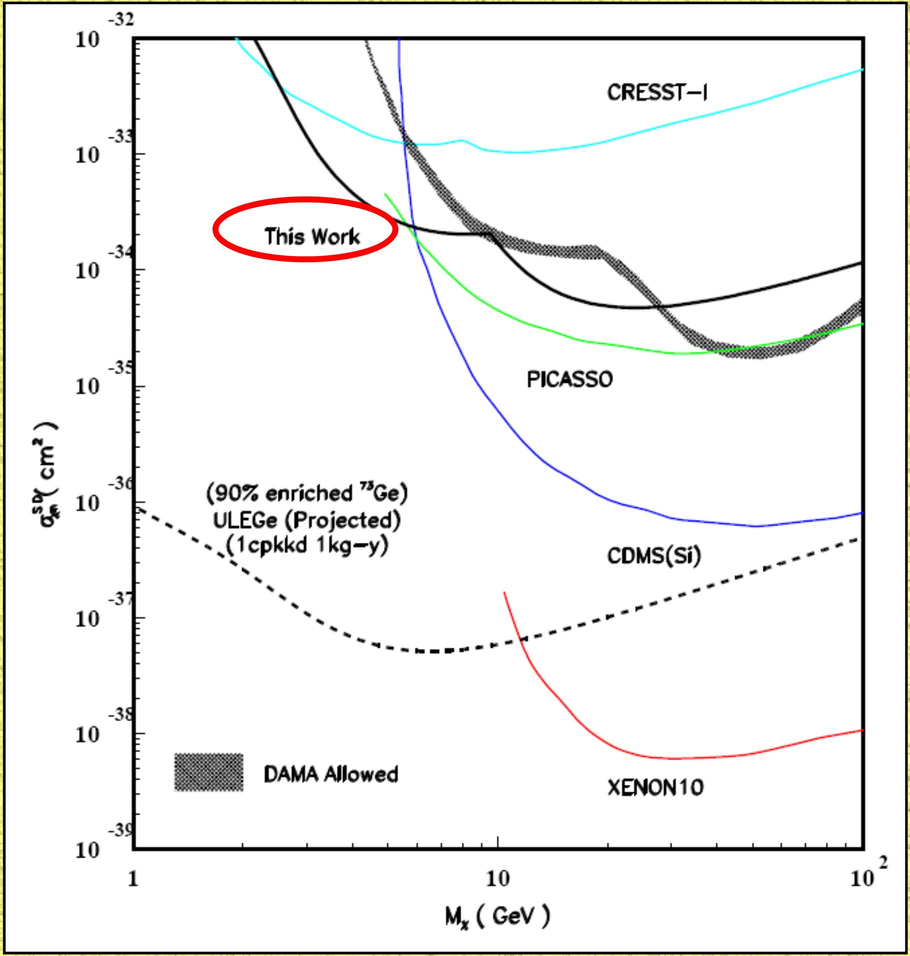
Exclusion Plot : Spin-Independent Couplings

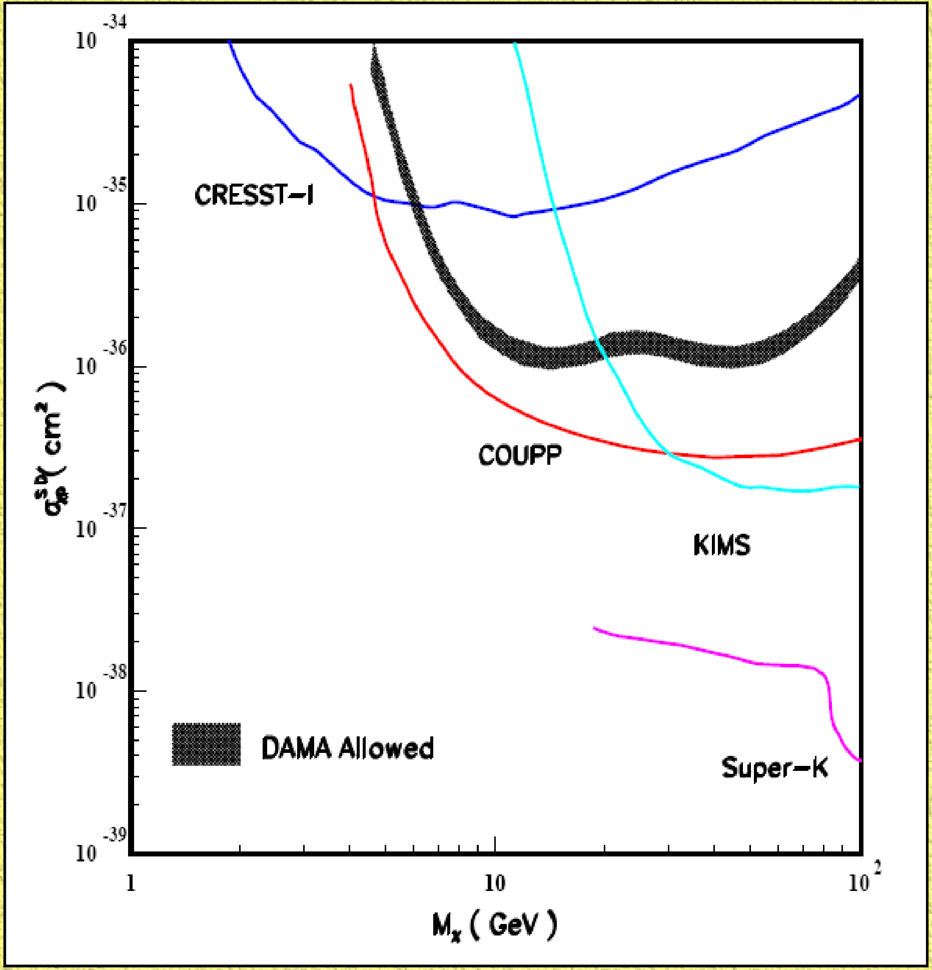


TEXONO : 20 g ULEGe at 220 eV threshold ⇒ low WIMP masses *[PRD 2009]*

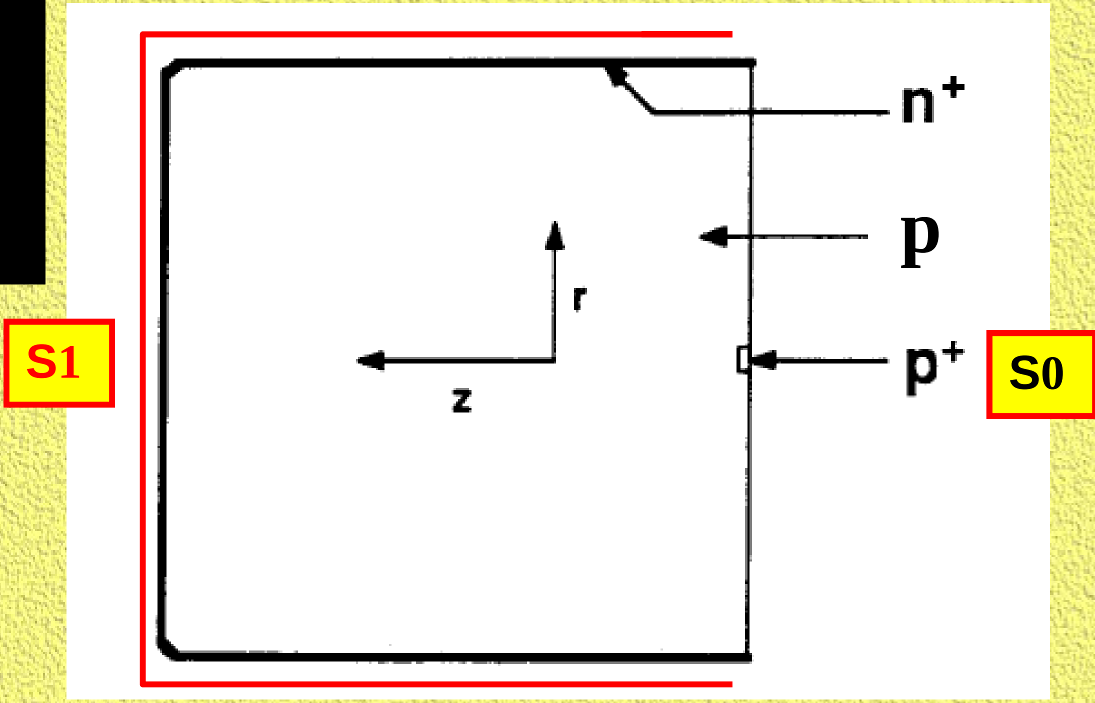
Data Taking at KS with 500g Point-Contact Ge Underway

Exclusion Plot : Spin-Dependent Couplings





Detector Scale-up Plans: Point Contact Ge Detector



- 500-g, single-element, modified coaxial HPGe design, inspired by successful demonstration of Chicago group (nucl-ex/0701012)
- Position-sensitive from drift-profile pulse shape
- Dual-electrode readout and ULB specification
- Delivered July 2008, KS data taking November 2008.

New Opportunities :
Excellent Candidate Site for Underground Lab. at 四川錦屏, China

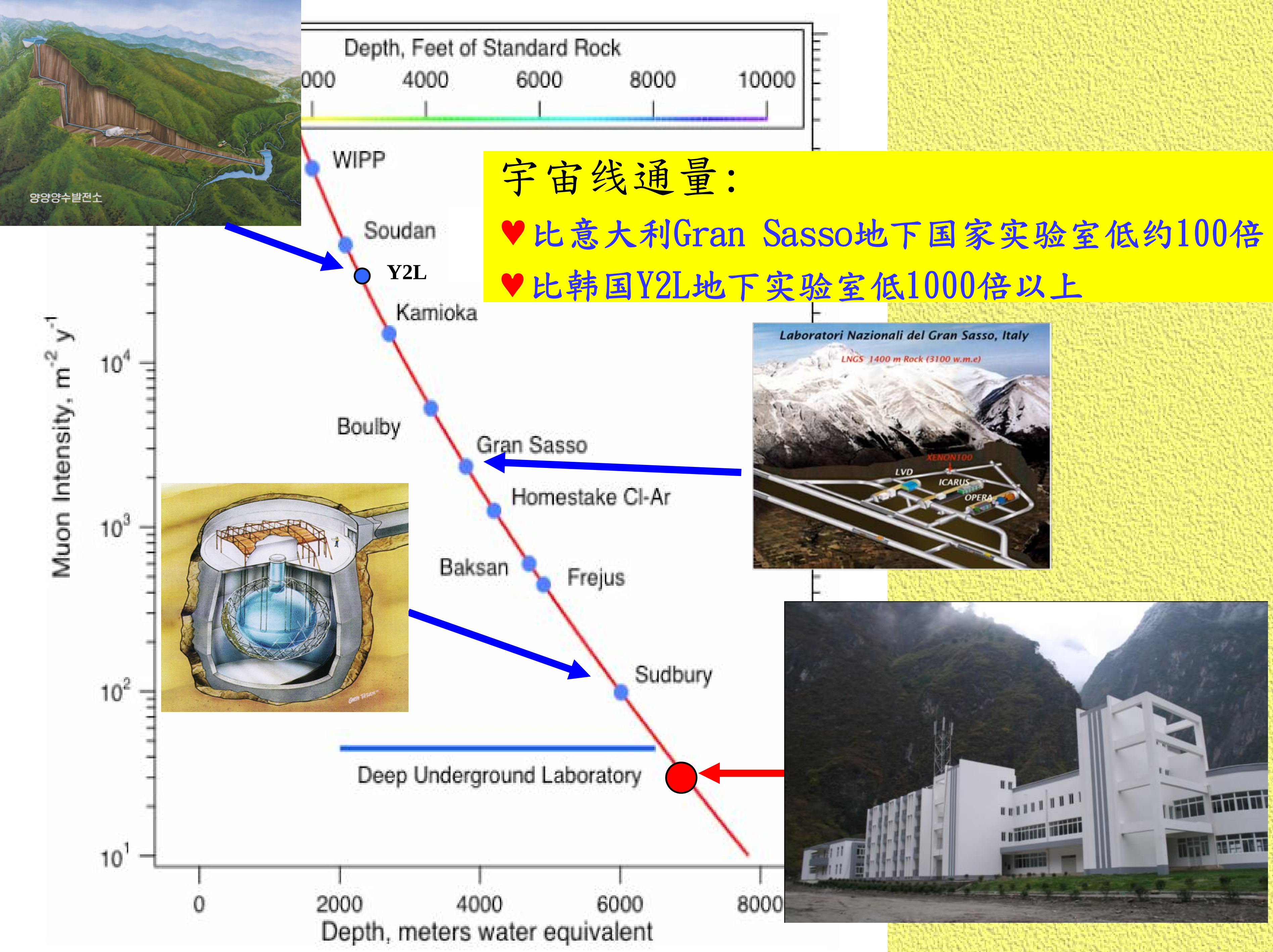
四川涼山彝族自治州冕寧縣
錦屏山

穿越锦屏山的锦屏二级水电站引水隧洞的最大埋深为2525米，四条隧洞的总长度超过了70公里，组成了世界规模最大的发电引水隧洞群。图为一号隧洞的TBM掘进机作业场景。（刘渝 喻安谋摄影报道）

♥ 17 km drive-access road tunnel with >2 km rock overburden !

宇宙线通量：

- ♥比意大利Gran Sasso地下国家实验室低约100倍
- ♥比韩国Y2L地下实验室低1000倍以上



Summary & Outlook

- **Missing Energy Density Problem** is the most intriguing & important one in basic science.
- Some tangible leads & lines of attack already exist for Dark Matter Problem
- **WIMPs** & **Axions** are two of the most popular candidates for Cold Dark Matter, motivated independently in Particle Physics
- Wide spectrum of experimental techniques pursued
- Several **anomalous results** which can be CDM-induced
- Competitive sensitivities in **TEXONO** on direct searches ⇨ New Underground Lab. at Sichuan soon
- ***Strong Potentials for Surprises*** in both Theory & Expts