Dark Matter WIMPs & Axions Experiments

- **Evidence and Candidates of Dark Matter**
- **Direct and Indirect Searches of WIMPs**
- **PAMELA/ATIC/DAMA Anomalous Results**
  [+ talks Bi XJ ; Shan CL]
- **TEXONO Results on Low Mass WIMPs**
  [+ talk Lin ST]
- **Axions** *(if time permits)*

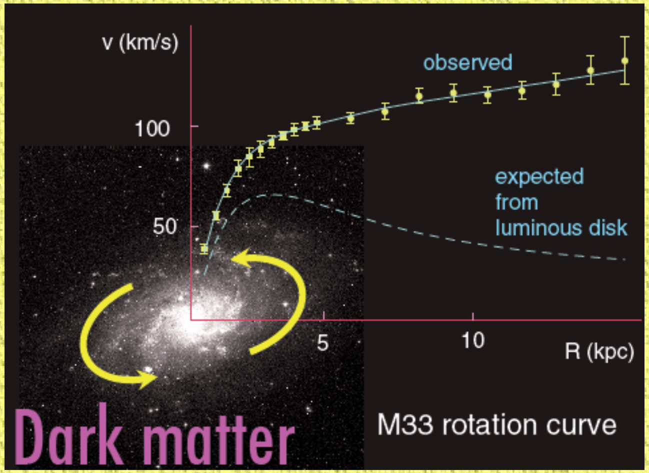
Henry T. Wong / 王子敬

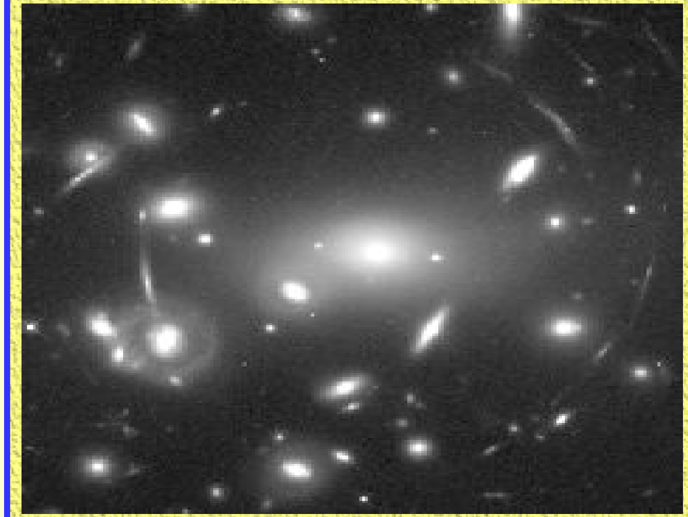
May 2009

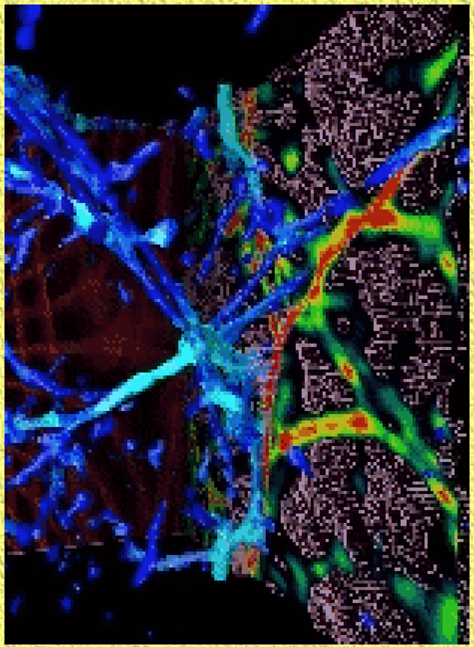
@

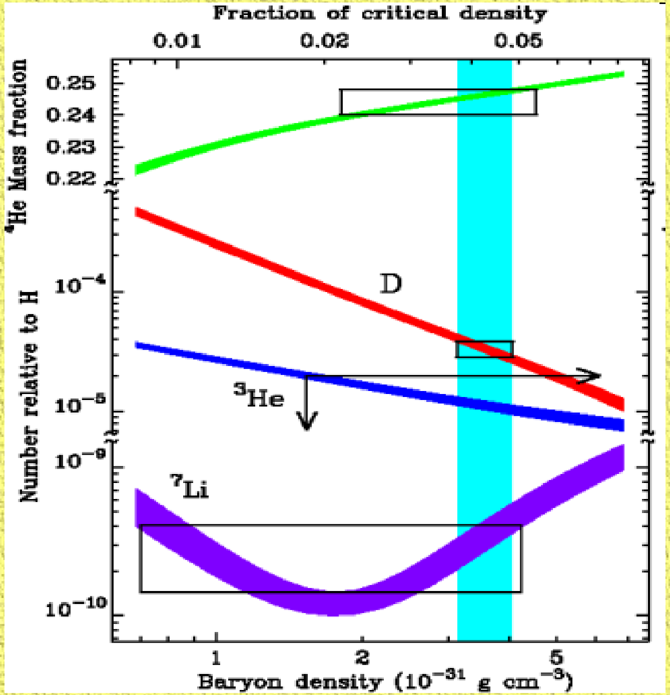
Evidence for Dark Matter

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

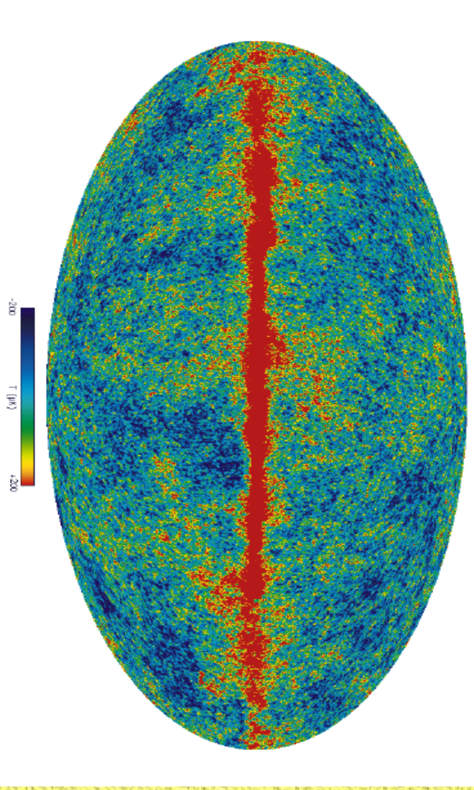


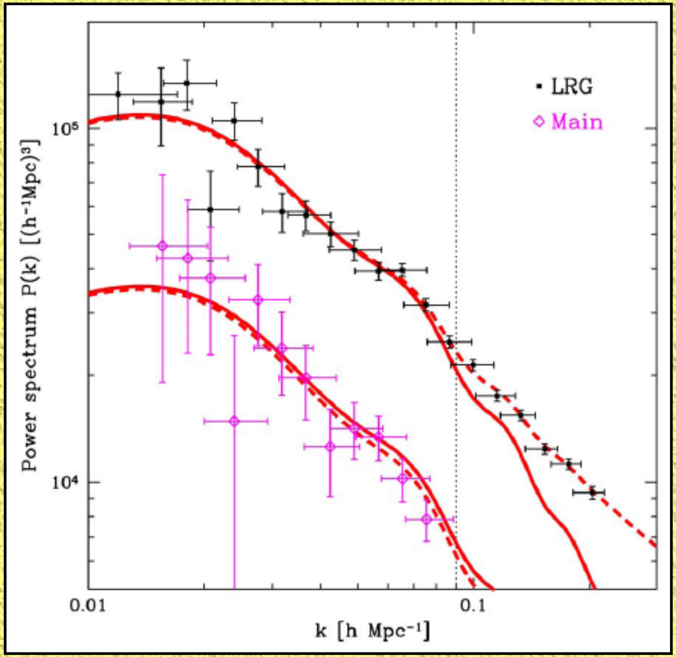




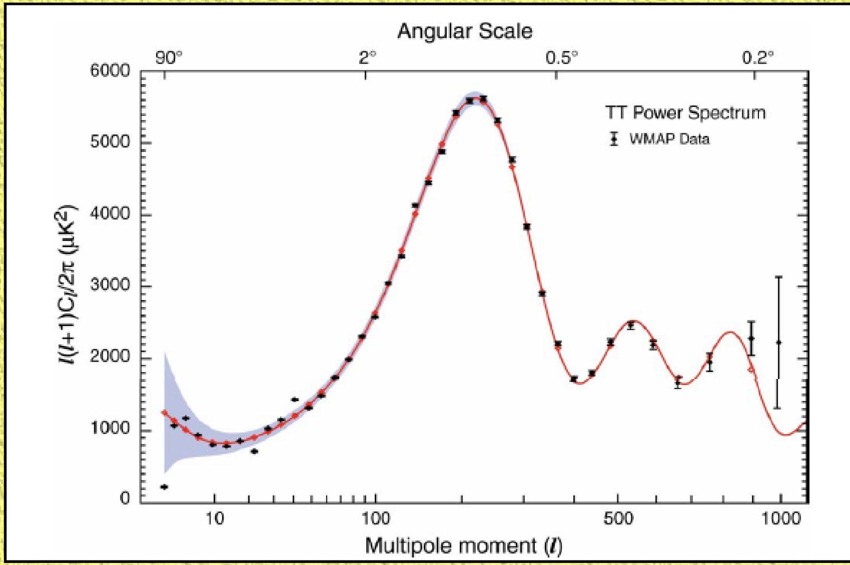


Fraction of critical density
0.01
0.02
0.05
^{4}He Mass fraction
0.25
0.24
0.23
0.22
Number relative to H
10^{-4}
10^{-5}
10^{-9}
10^{-10}
D
^{3}He
^{7}Li
1
2
5
Baryon density (10^{-31} g cm^{-3})



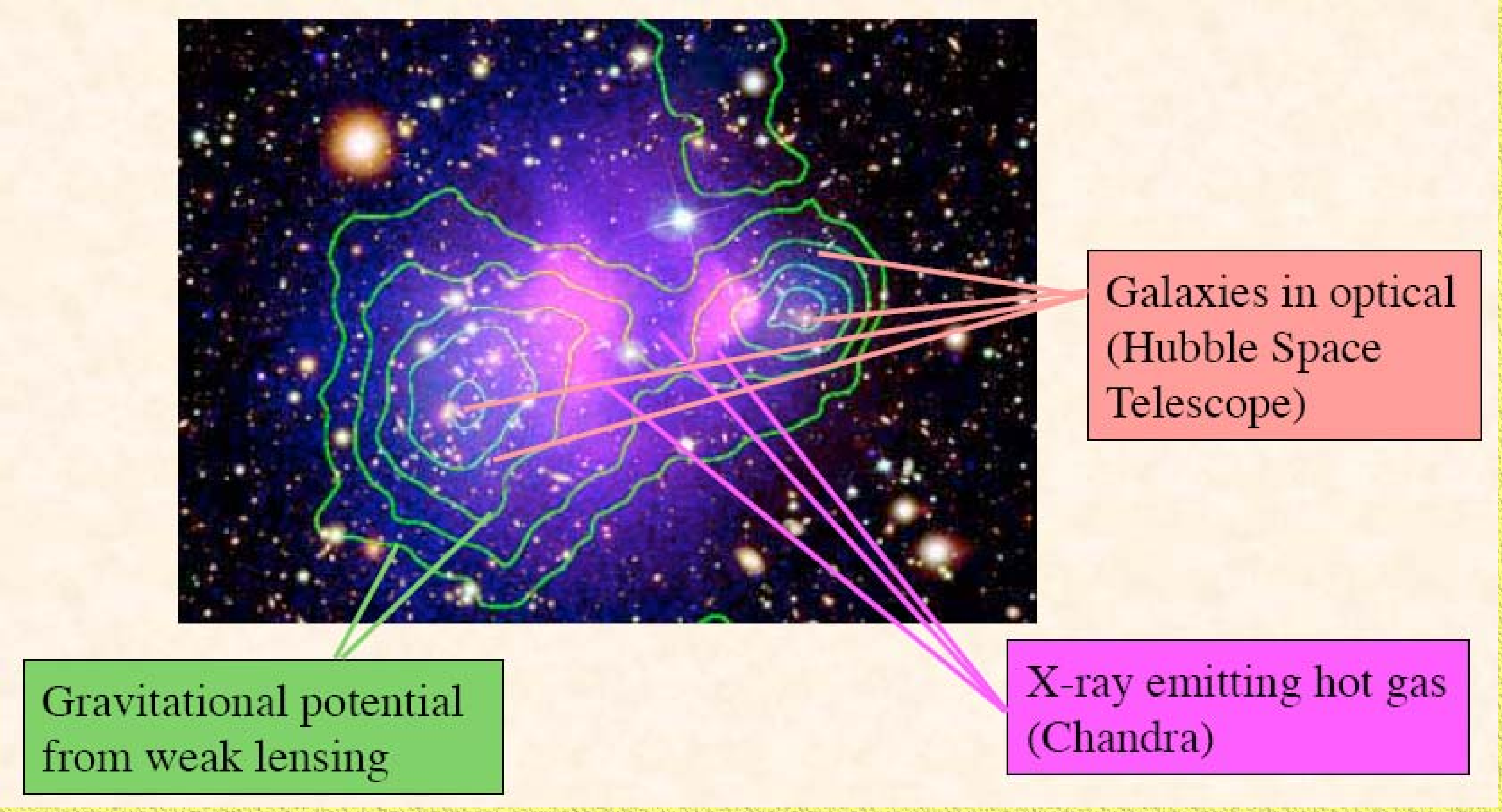


LRG
Main
Power spectrum P(k) [(h^{-1}Mpc)^3]
10^5
10^4
0.01
0.1
k [h Mpc^{-1}]



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

Dark Matter is DARK (not interacting electromagnetically)
And NOT modified Gravity …….



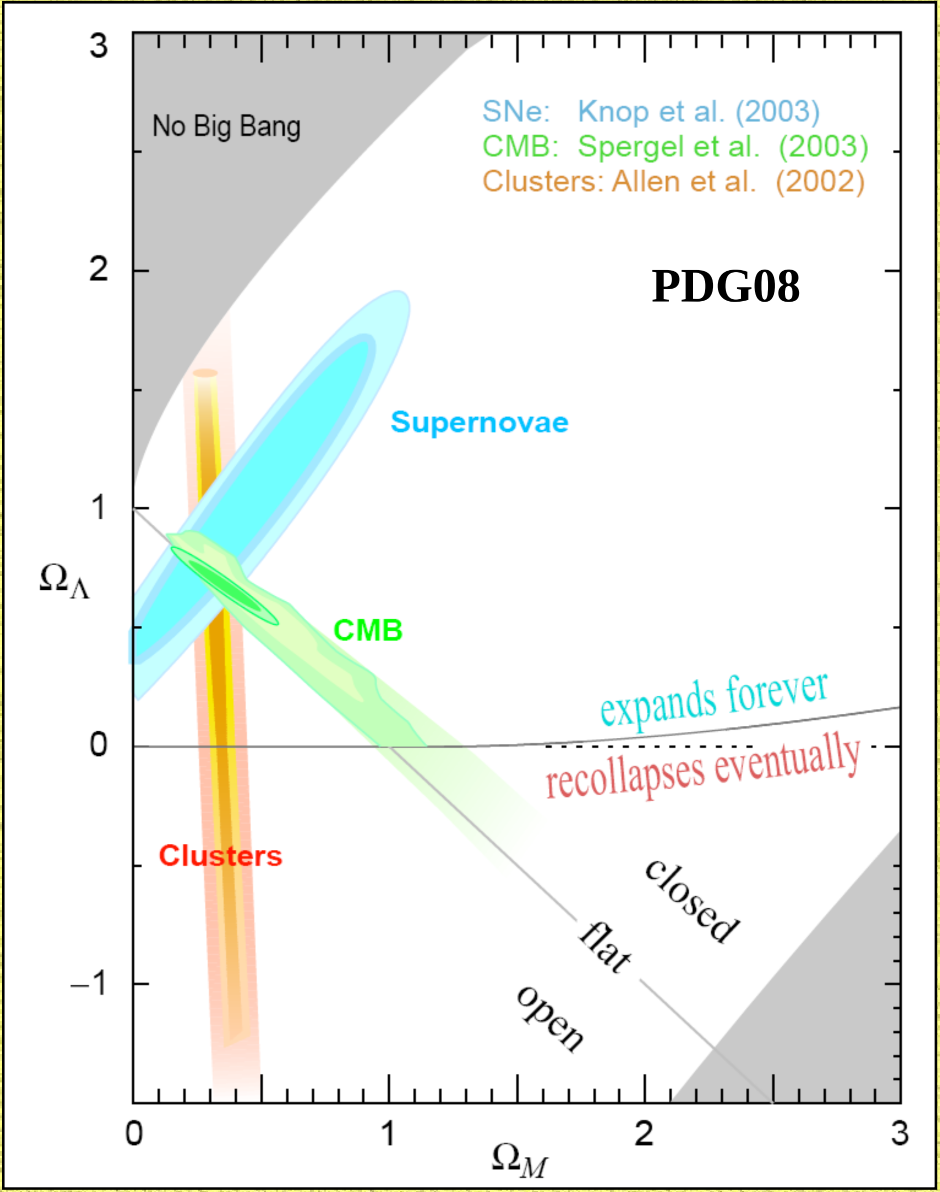
Combined Constraints :

h = 0.71 ± 0.04

Cosmological constant	$\Omega_\Lambda h^2 = 0.354 \pm 0.008$
Matter ($p \approx 0$)	$\Omega_m h^2 = 0.1369 \pm 0.003$
Radiation ($p = \rho/3$)	$\Omega_r h^2 = 2.47 \times 10^{-5}$

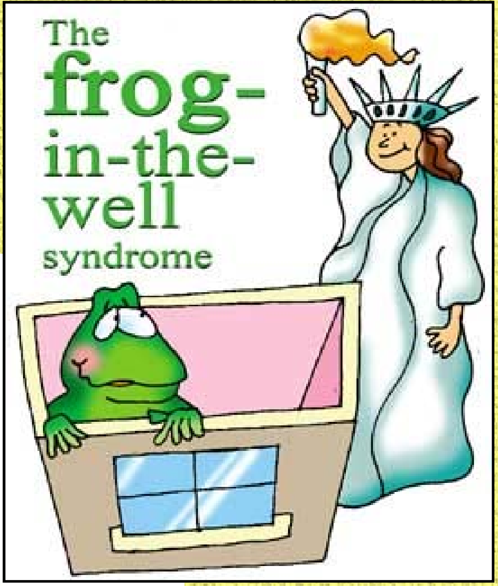
Matter:

- ordinary matter $\Omega_b h^2 = 0.02265 \pm 0.00059$
- hot dark matter $\Omega_\nu h^2 < 0.065$ (95% C.L.)
- cold dark matter $\Omega_c h^2 = 0.1143 \pm 0.0034$

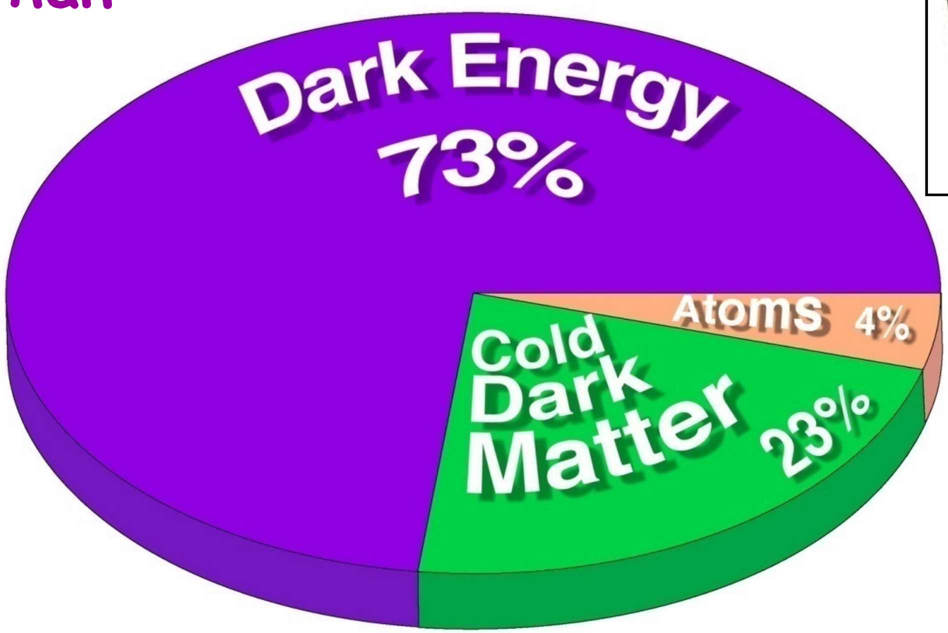


$$\Omega_\Lambda = 0.73 \pm 0.04, \qquad \Omega_m = 0.27 \pm 0.04$$

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



Dark Energy : " We know less than Nothing !"



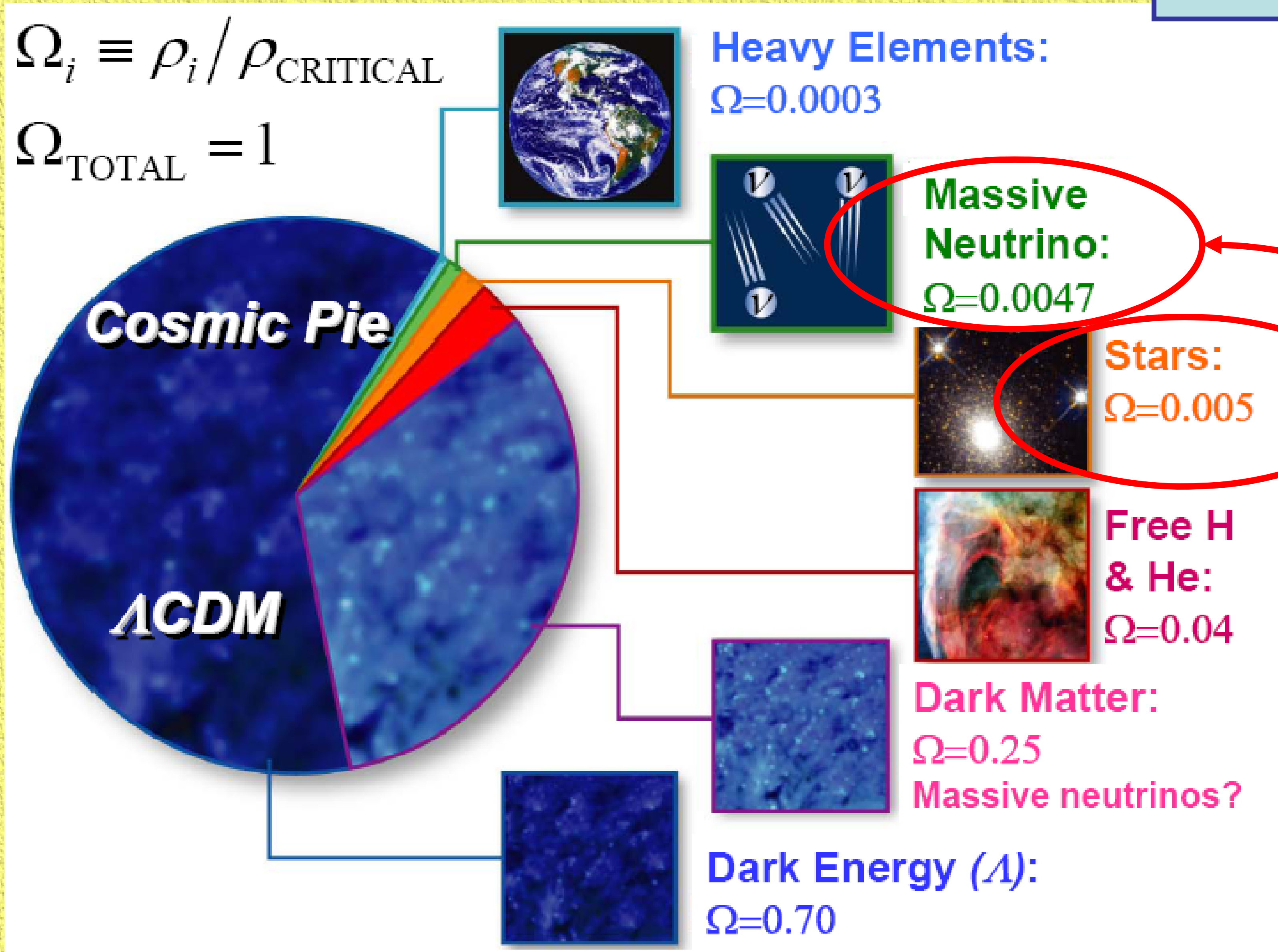
← Standard Model Matter : Understood

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

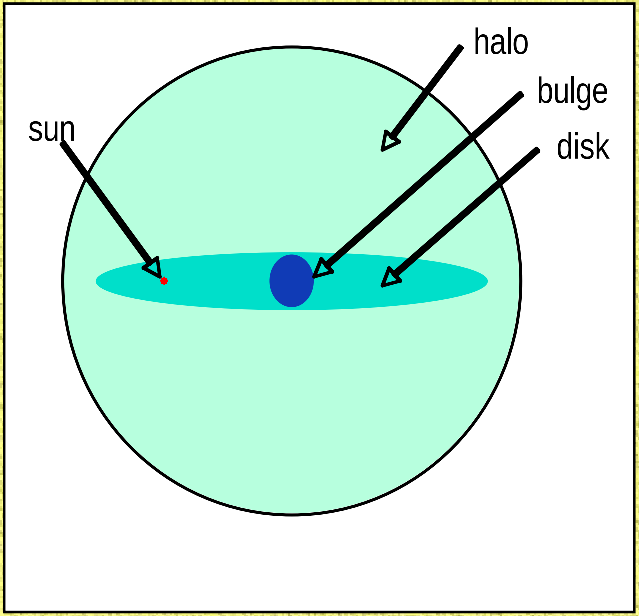
Or ….

- *The Ultimate Copernicus Principle !!*

at least as much neutrinos by mass as visible matter !



Properties of a Good Cold Dark Matter Candidates:

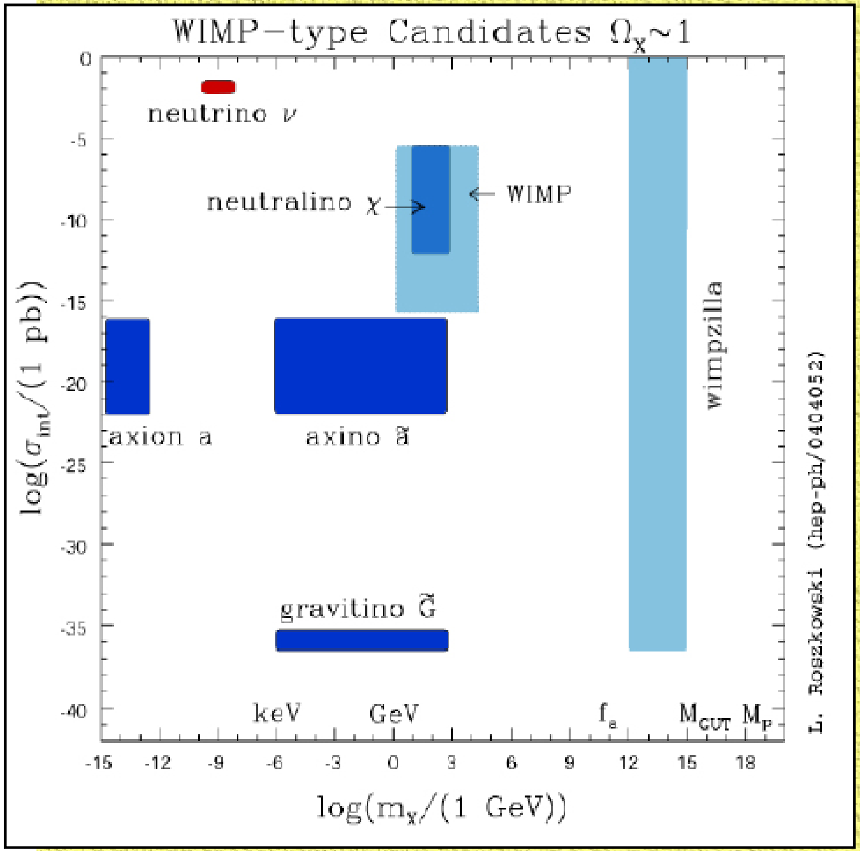


Dark Matter gravitationally bounded in galactic halo

- ✓ 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

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

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

- Leaves a relic abundance:

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

! *IF* σ_A ~ **electroweak scale**

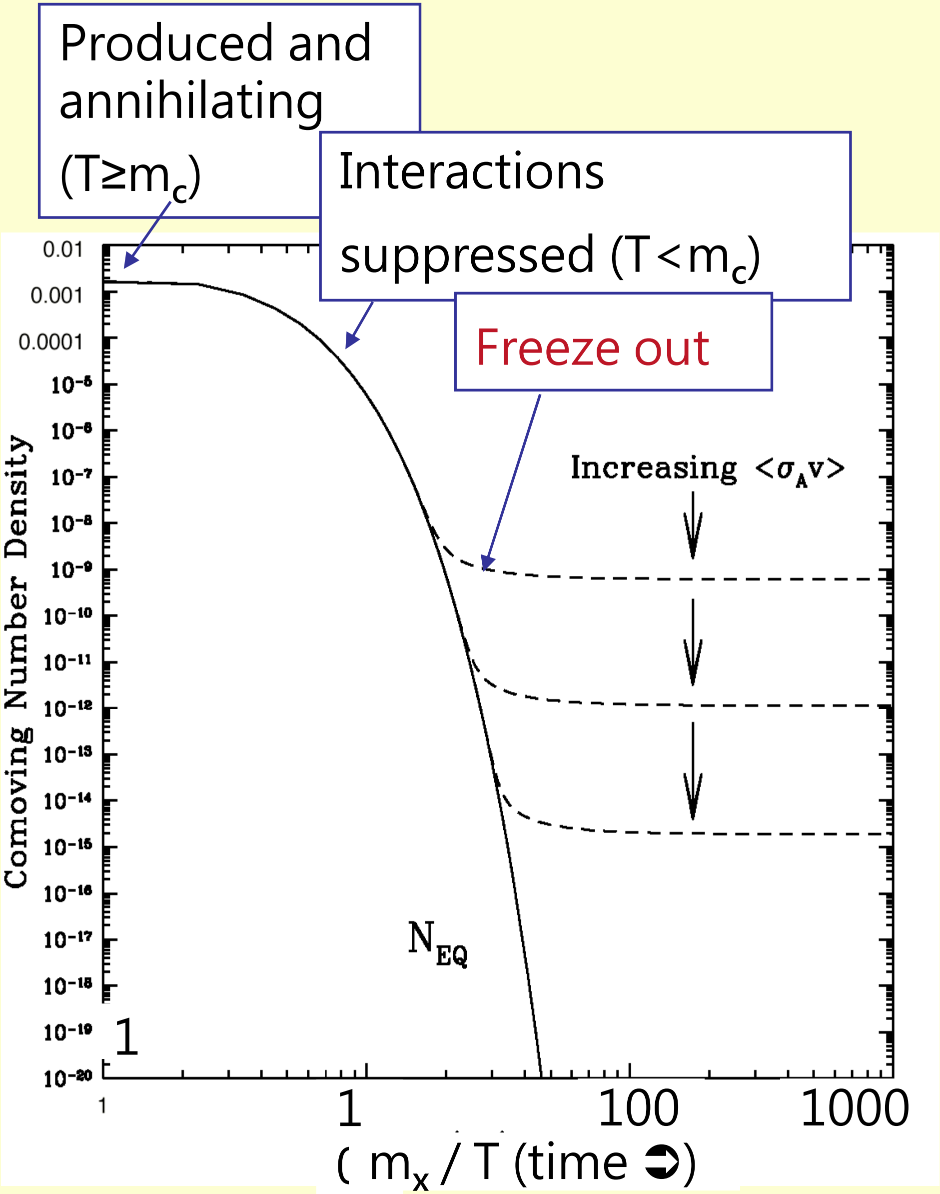
$$\sigma_{ann.} \approx \text{a few pb} \approx \alpha_W^2 / M_W^2$$

THEN $\Omega_\chi \sim 0.3$

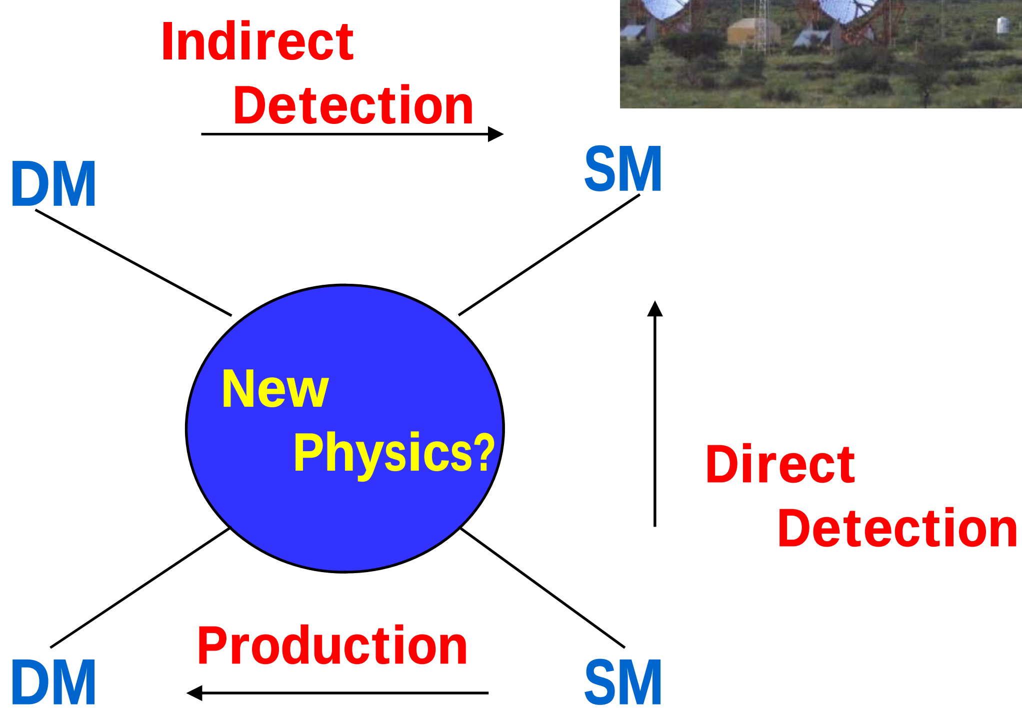
[coincidence or miracle ?!]

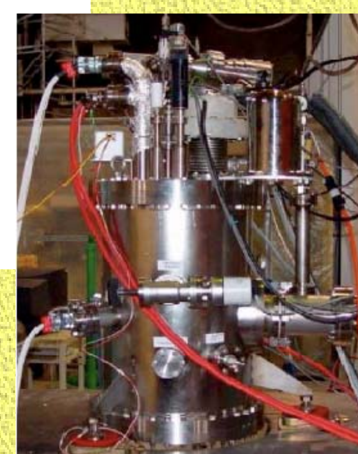
$\Rightarrow$ *WIMPs*

(no constraints on m_χ)



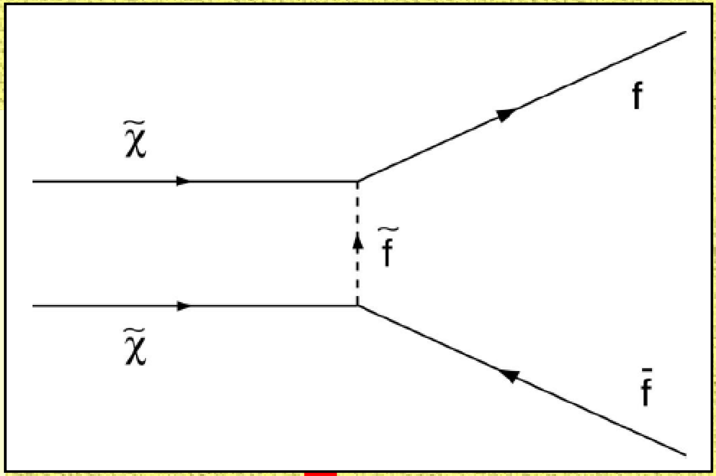
Dark Matter Detection

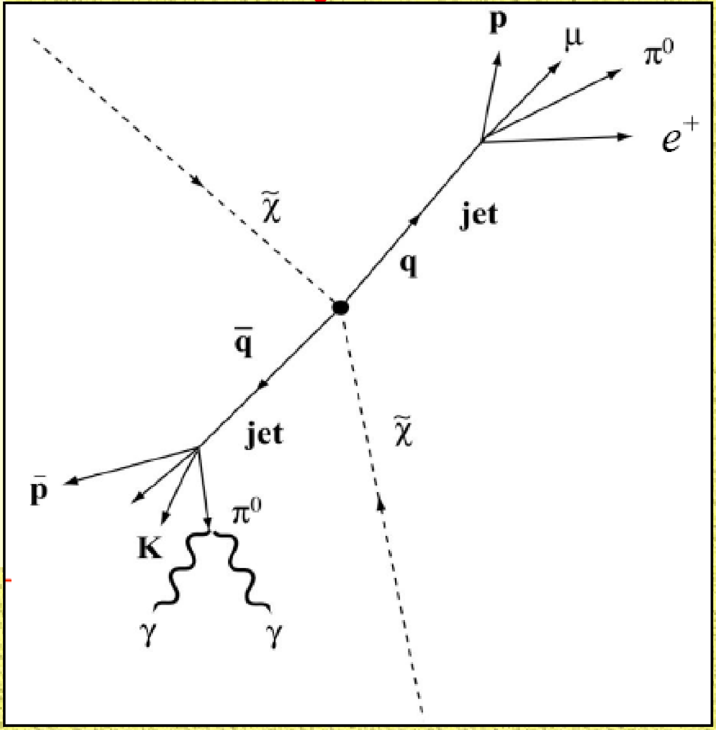




Indirect Detection of WIMP

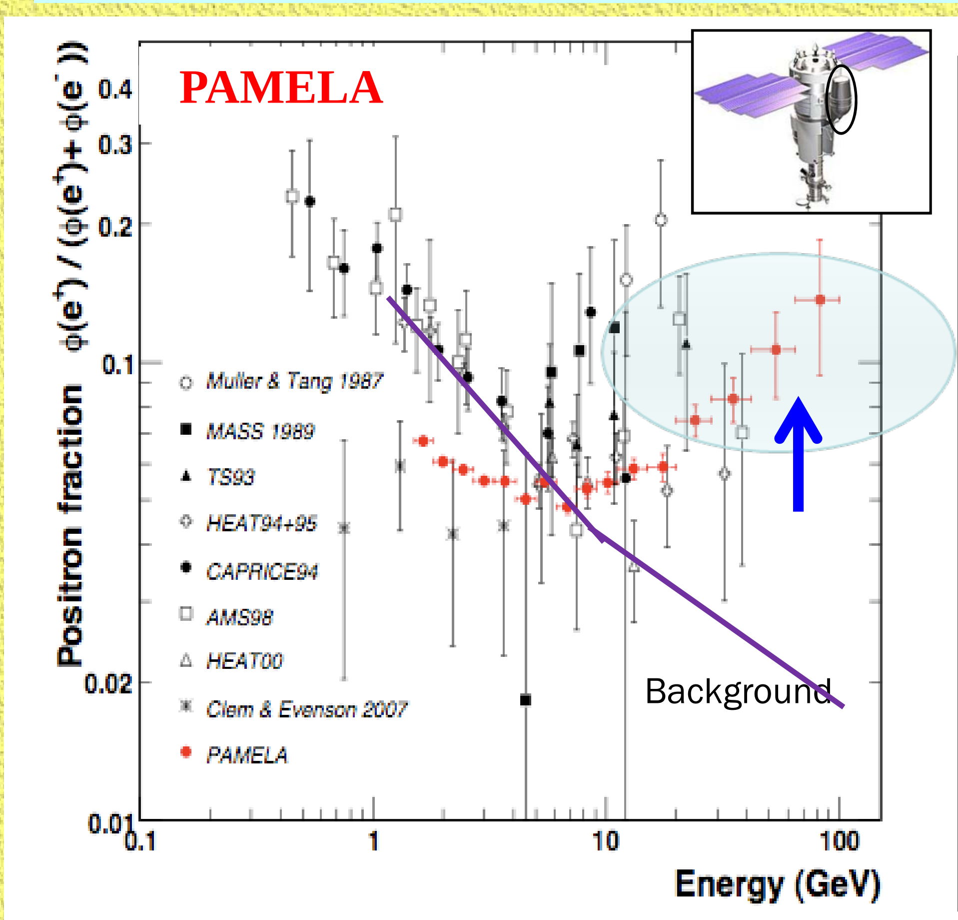
- through their annihilation products
- Signals ⇨ high-energy neutrinos, anti-protons, positrons & photons
- Sources ⇨ Sun, Earth, Galactic Center, Milky Way Halo, Stars, External Galaxies
- HE neutrinos from Sun/Earth or anomalous γ-rays peaks ⇨ smoking gun signatures
- Anomalous spectral distributions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





Anomalous Cosmic Positron Spectrum

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



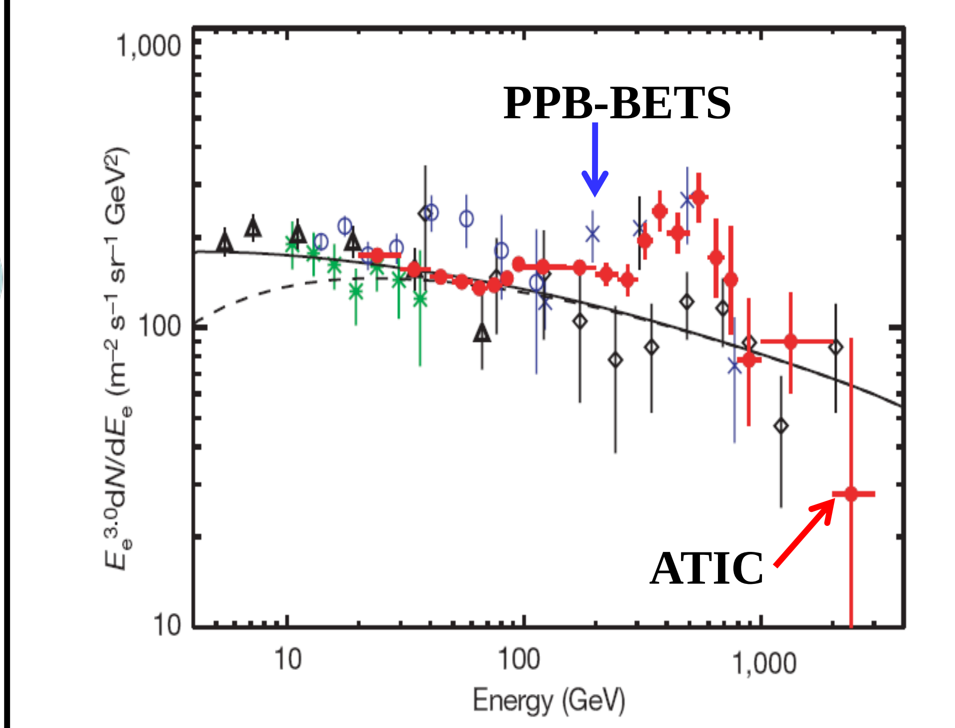


Figure 3 | ATIC results showing agreement with previous data at lower energy and with the imaging calorimeter PPB-BETS at higher energy. Th

Astrophysical Primary sources or WIMP-induced ??

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

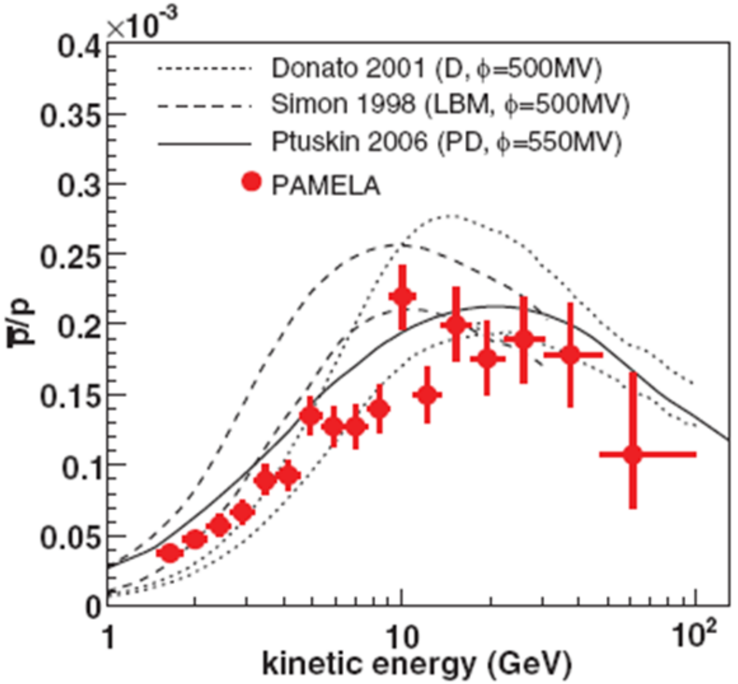


FIG. 3 (color). The antiproton-to-proton flux ratio obtained in this work compared with theoretical calculations for a pure secondary production of antiprotons during the propagation of cosmic rays in the galaxy. The dashed lines show the upper and lower limits calculated by Simon *et al.* [17] for the 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.

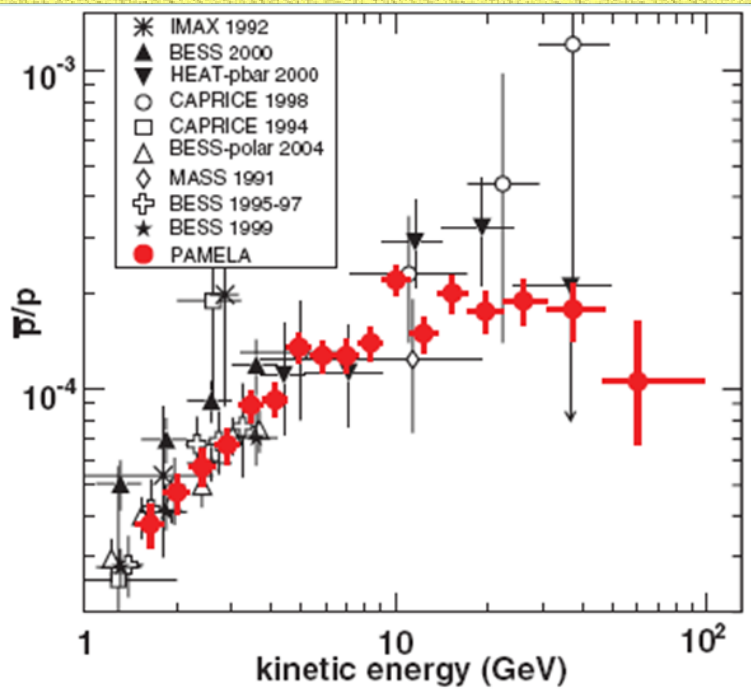


FIG. 4 (color). The antiproton-to-proton flux ratio obtained in this work compared with contemporary measurements [8–10,20–23].

Advanced Thin Ionization Calorimeter

ATIC

411

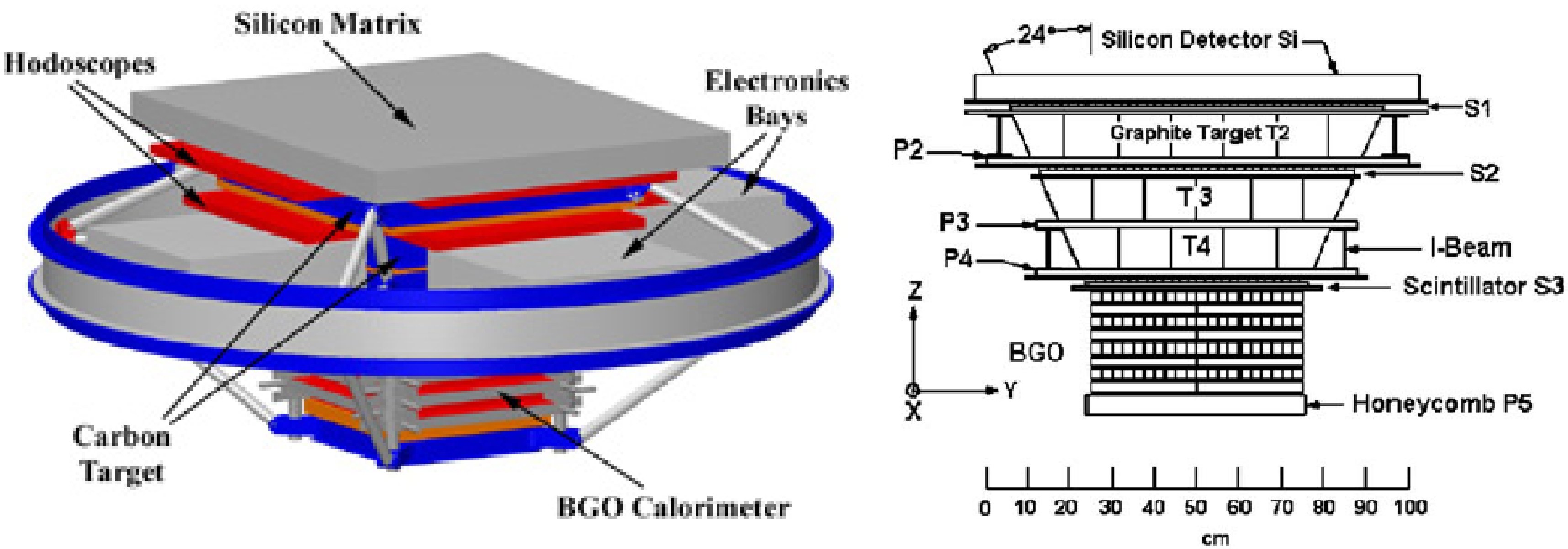
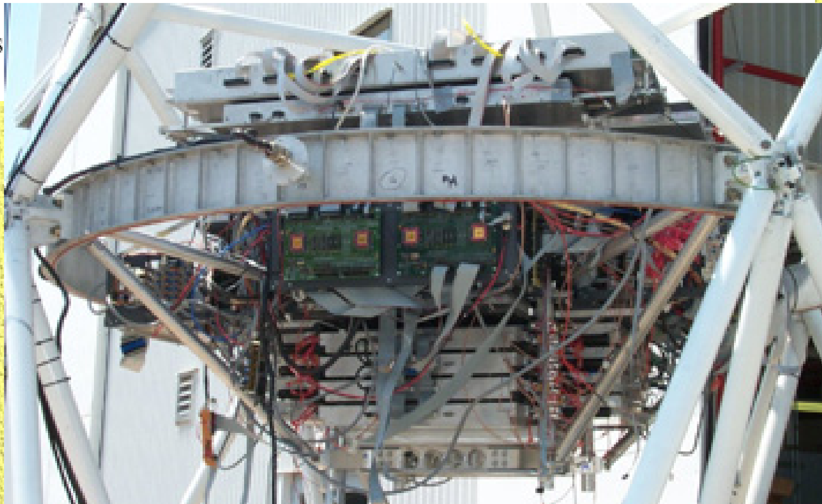


Fig. 1. 3D mechanical drawing (left) and 2D simulation s



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}**

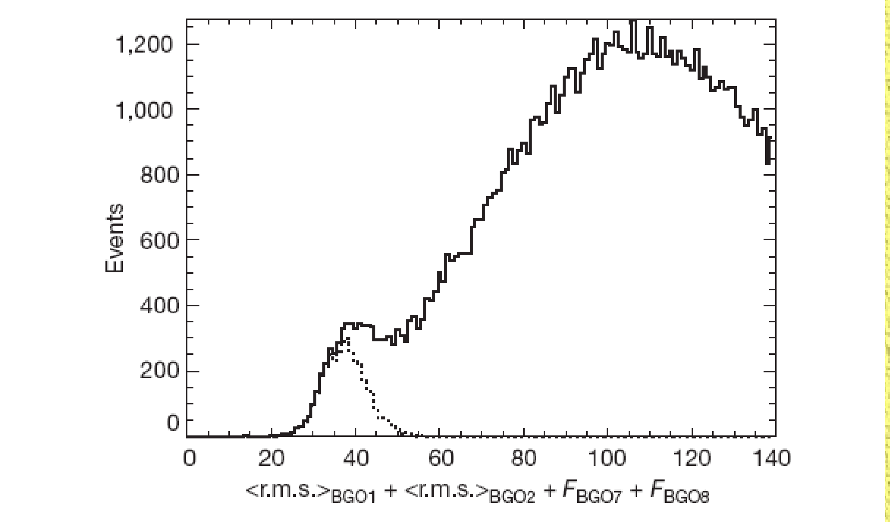
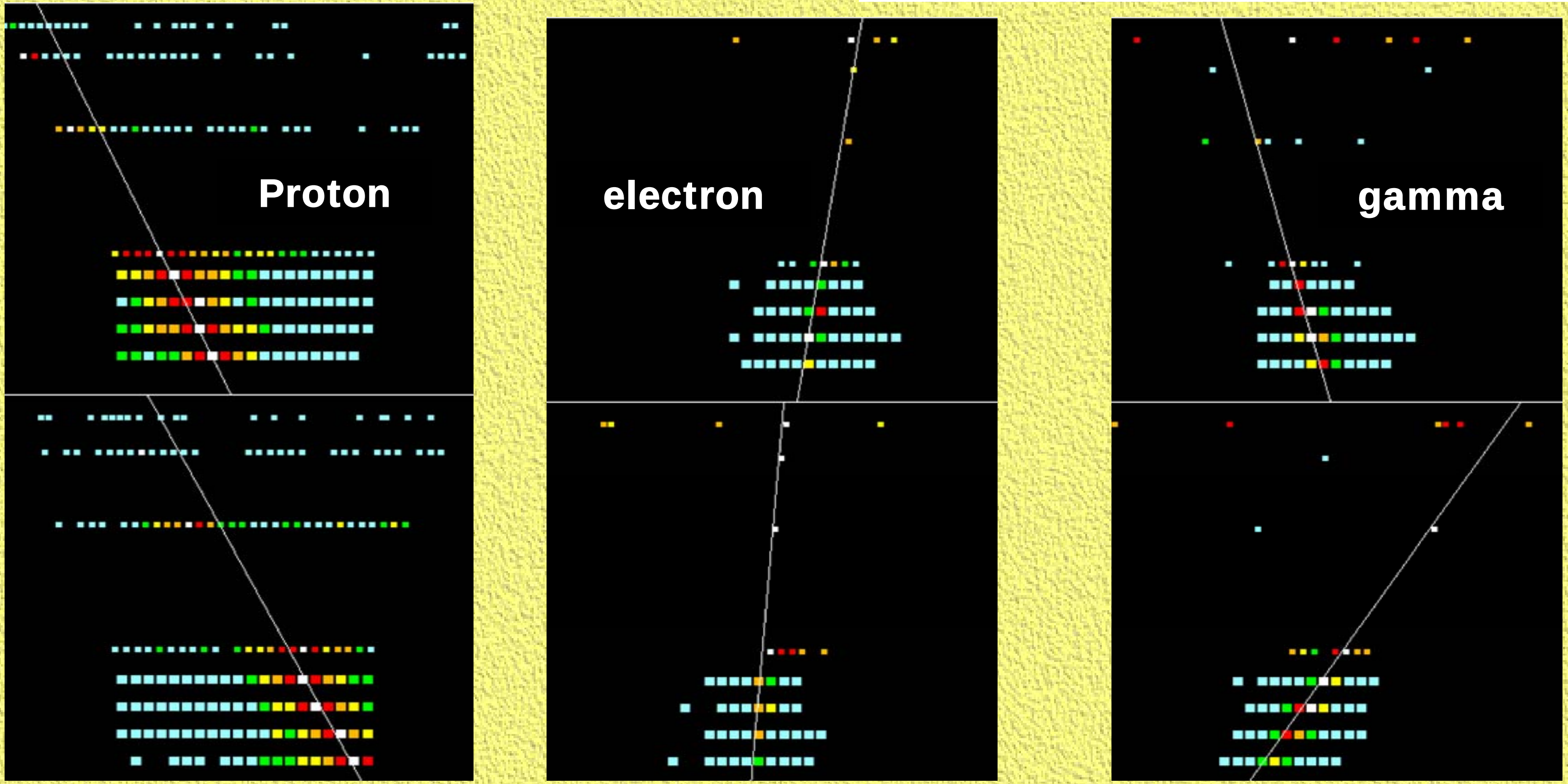


Figure 1 | Separation of electrons from protons in the ATIC instrument.



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).

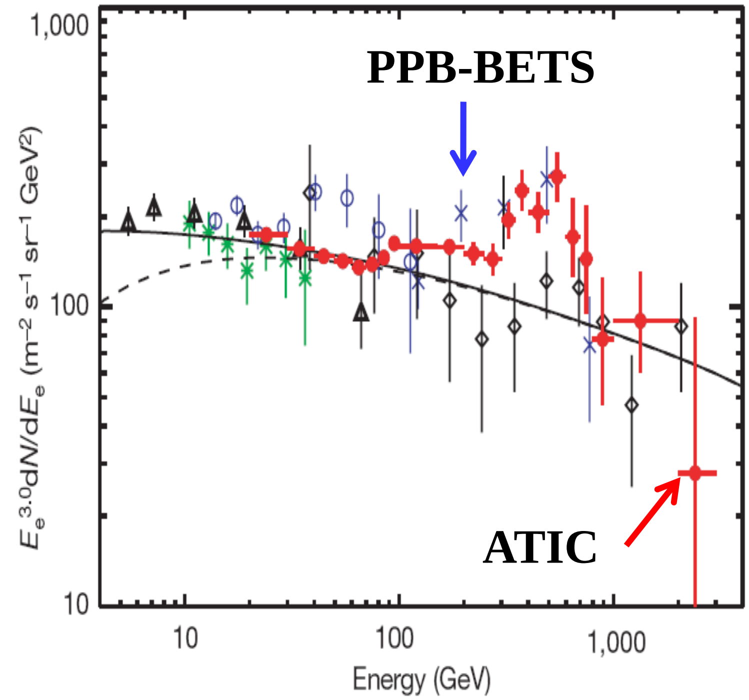
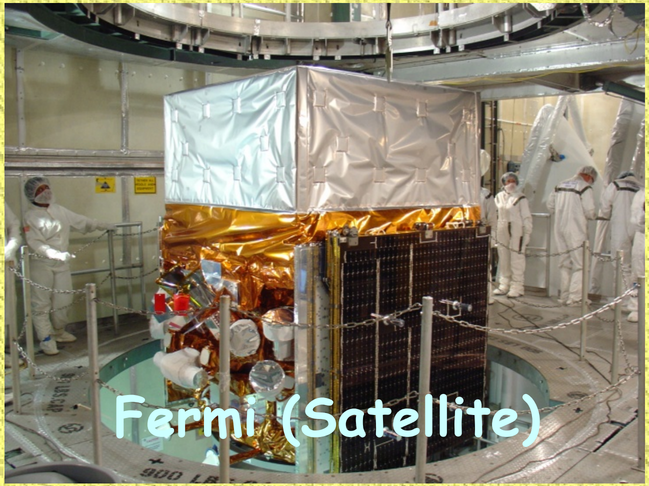
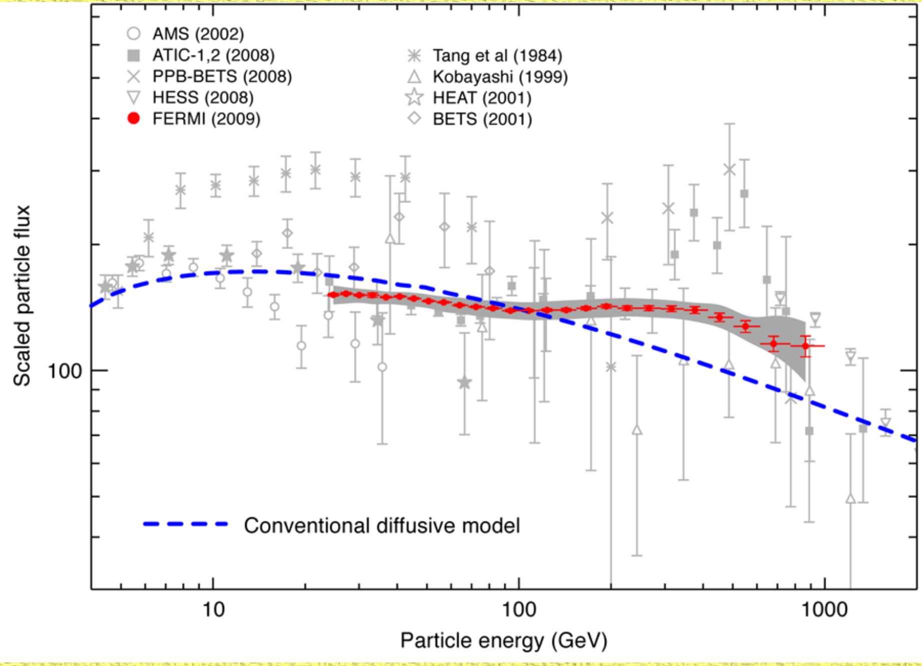


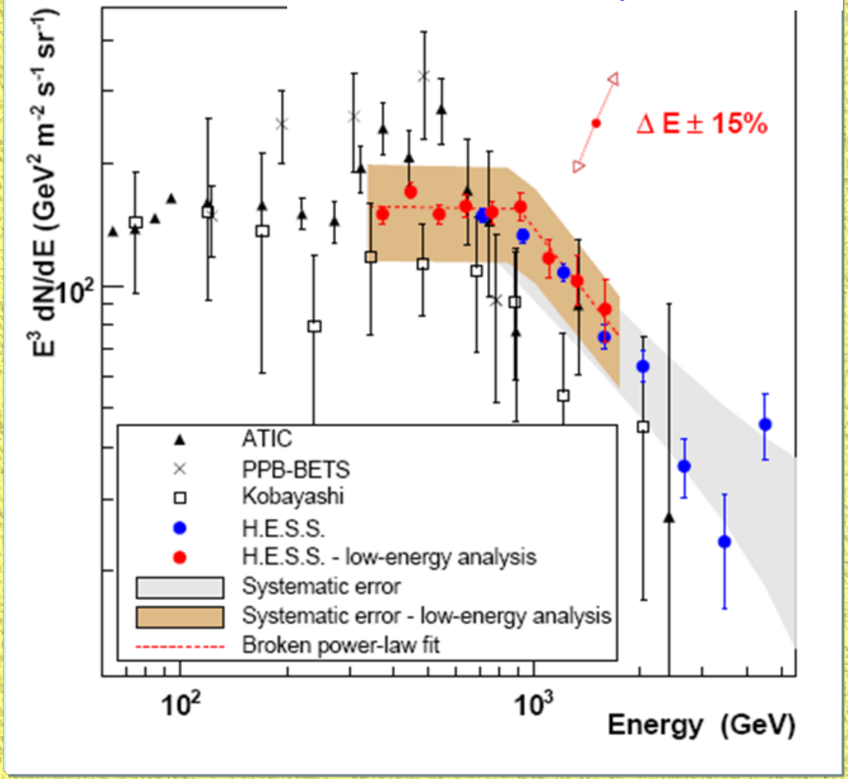
Figure 3 | ATIC results showing agreement with previous data at lower energy and with the imaging calorimeter PPB-BETS at higher energy. Th

But ! New May 2009 Results …..



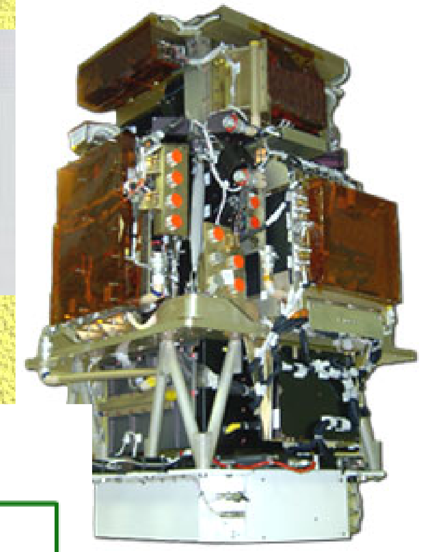
HESS (Air Cerenkov Telescope)

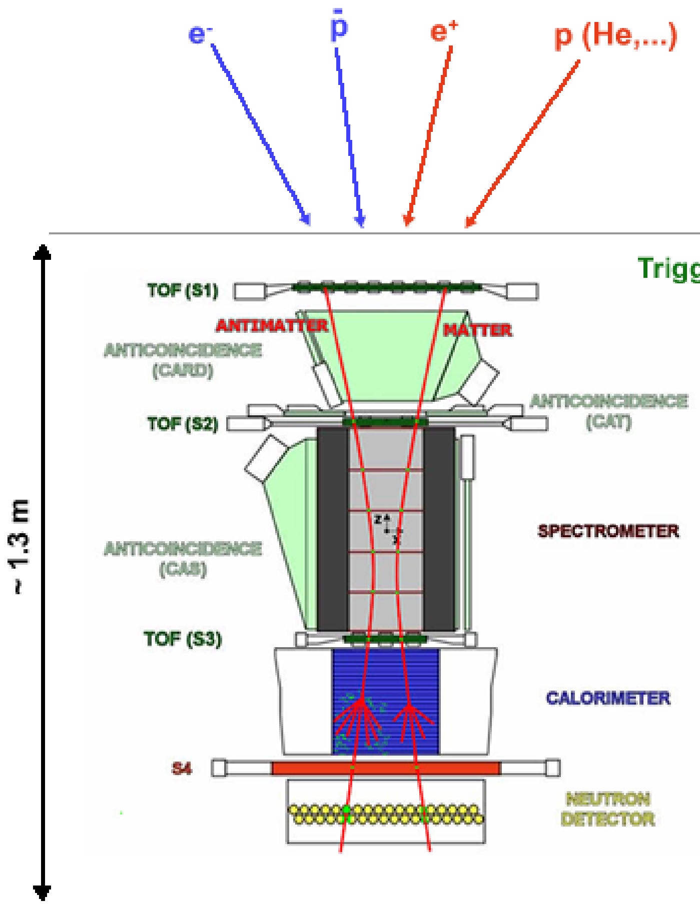




PaMeLa

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

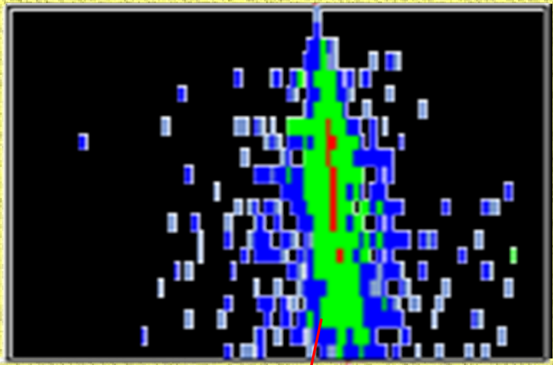
- Permanent magnet, 0.43 T
- 21.5 cm^2 sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MDR ~800 GV (6 plane) ~500 GV (5 plane)

Electron energy, dE/dx, lepton-hadron separation

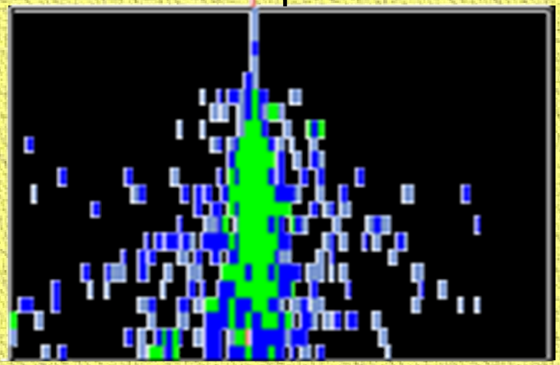
- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm^2 sr

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

51 GV positron

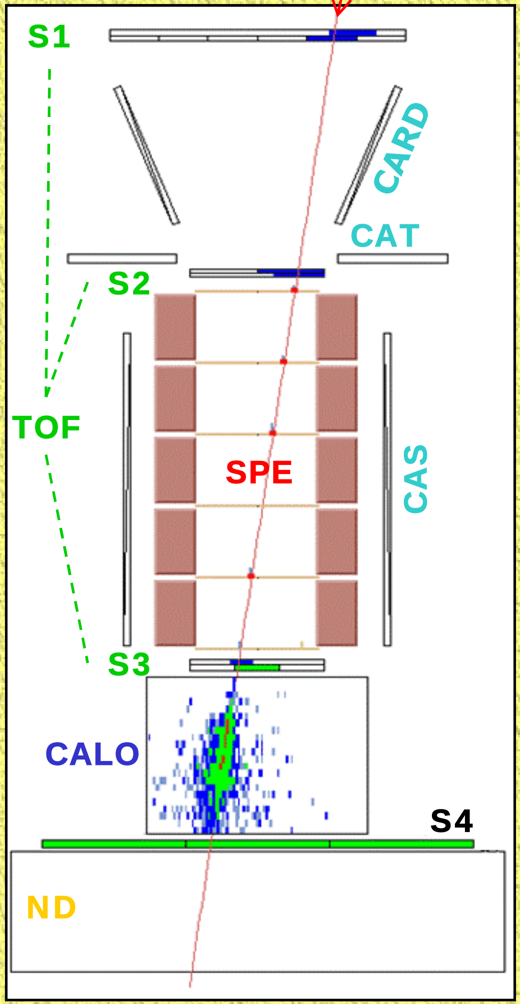


80 GV proton



e/p separation:

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



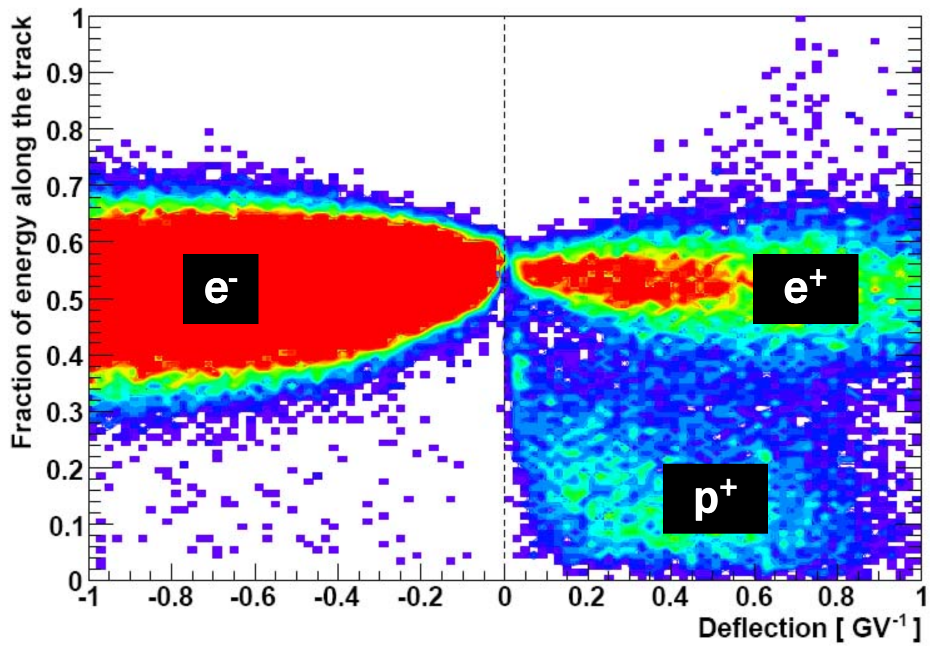


FIG. 1: **Calorimeter energy fraction** $\mathcal{F}$. The fraction of calorimeter energy deposited inside a cylinder of radius 0.3 Molière radii, as a function of deflection. d by extrapolating the particle track reconstructed by the spectr

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]

Vol 458 | 2 April 2009 | **doi:10.1038/nature07942**

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.

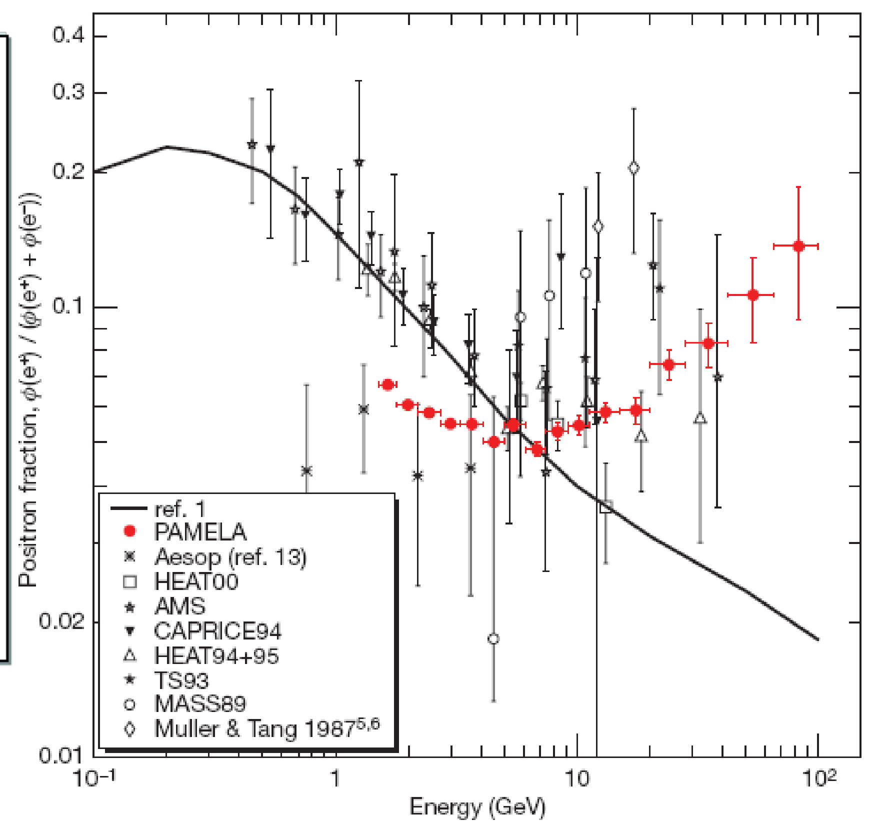
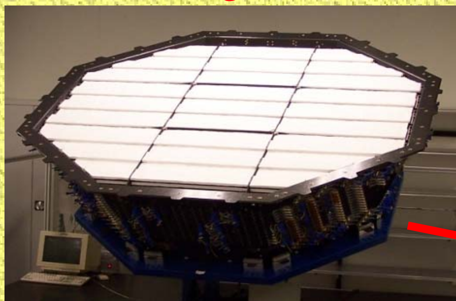


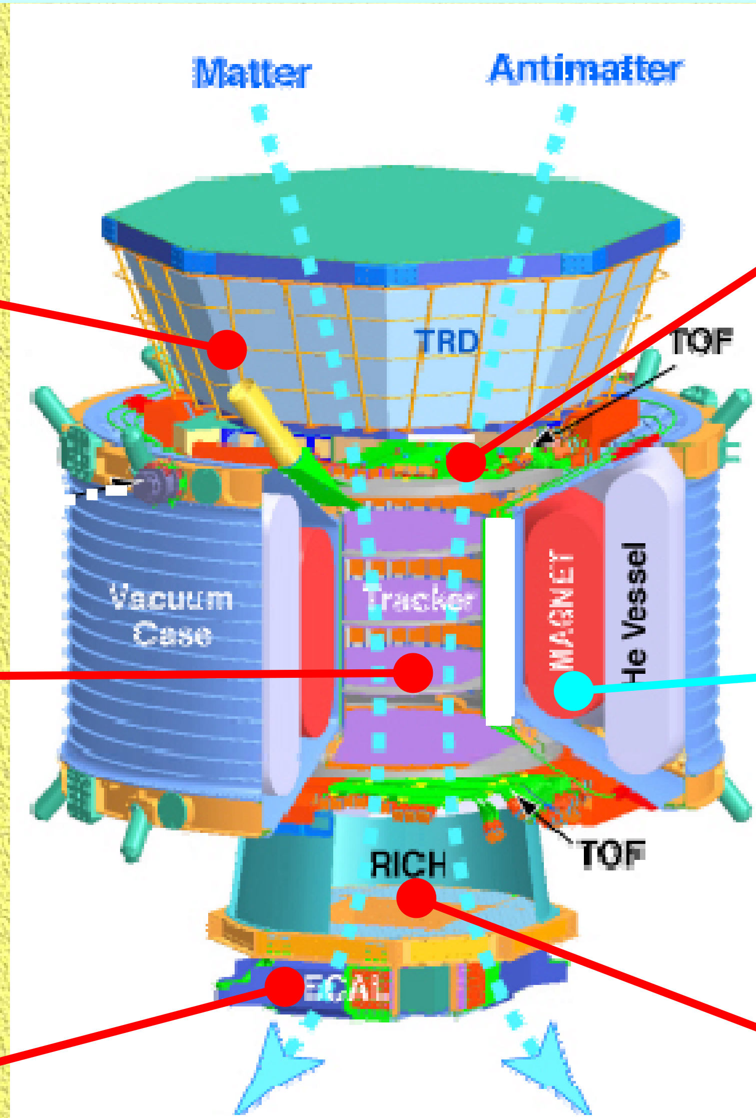
Figure 2 | PAMELA positron fraction with other experimental data and with secondary production model. The positron fraction measured by the

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

TRD
e

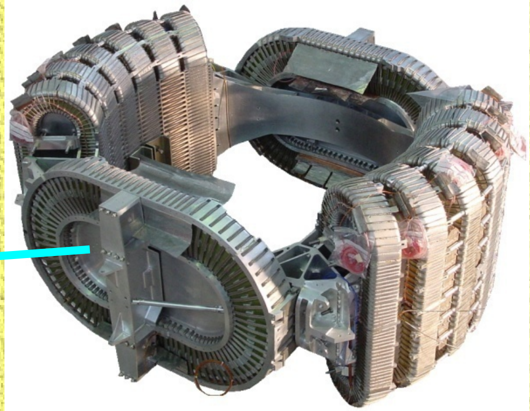


Time of Flight
v, Z



Silicon Tracker
Z, P

Magnet
P



Calorimeter
e, γ

RICH
v, Z

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

AMS-2 Sensitivities …

… charge determination till ~500 GeV

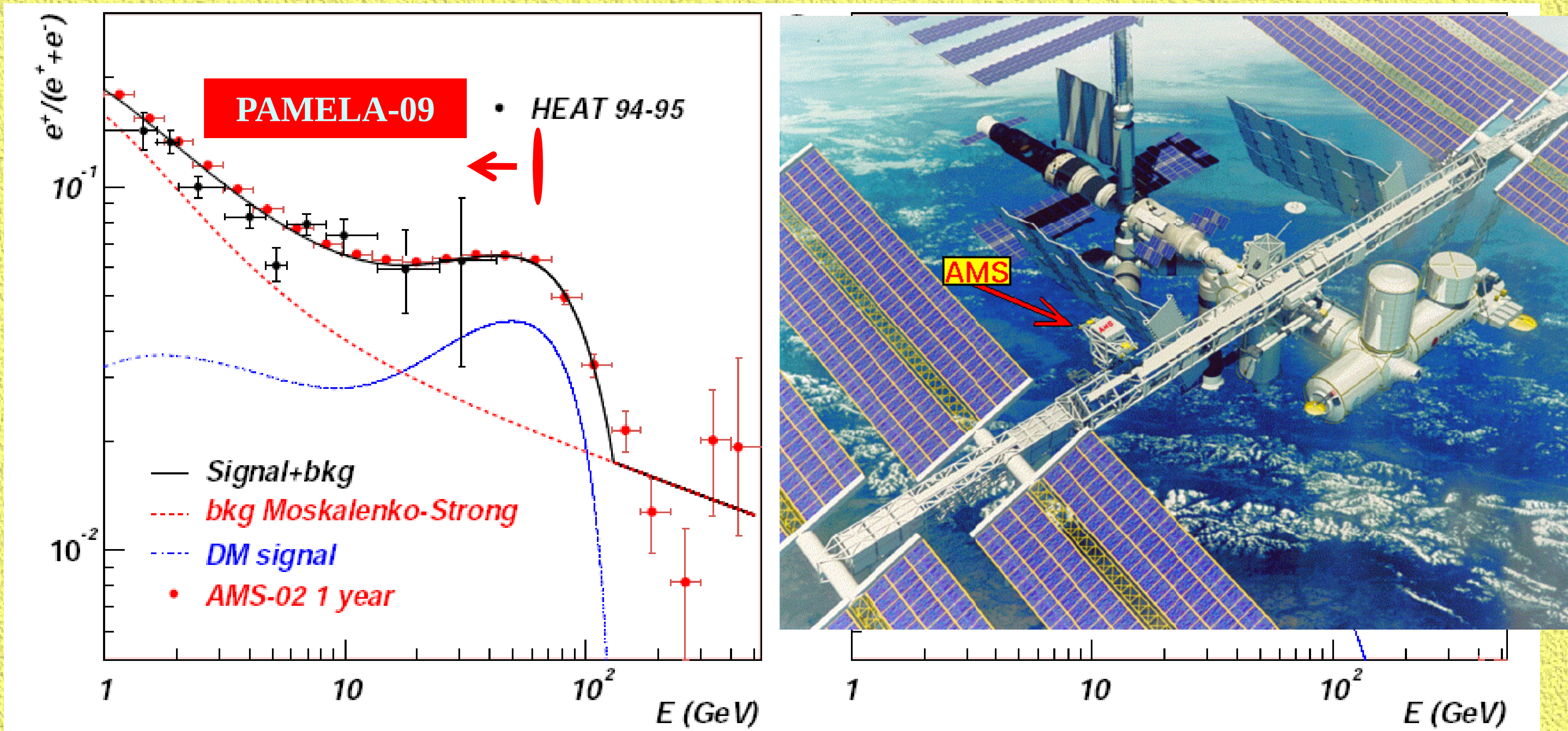
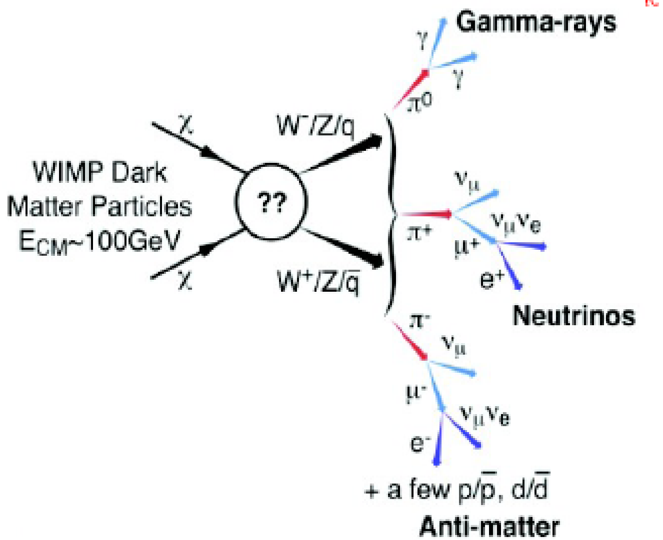


Fig. 1. AMS-02 e^+ fraction in the case of a primary e^+ from annihilating χ [11]

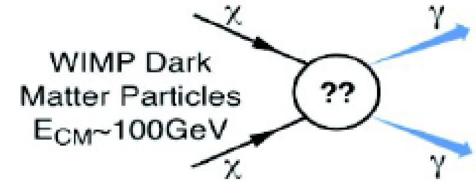
γ-rays from WIMP annihilation

Continuum spectrum with cutoff at M_χ



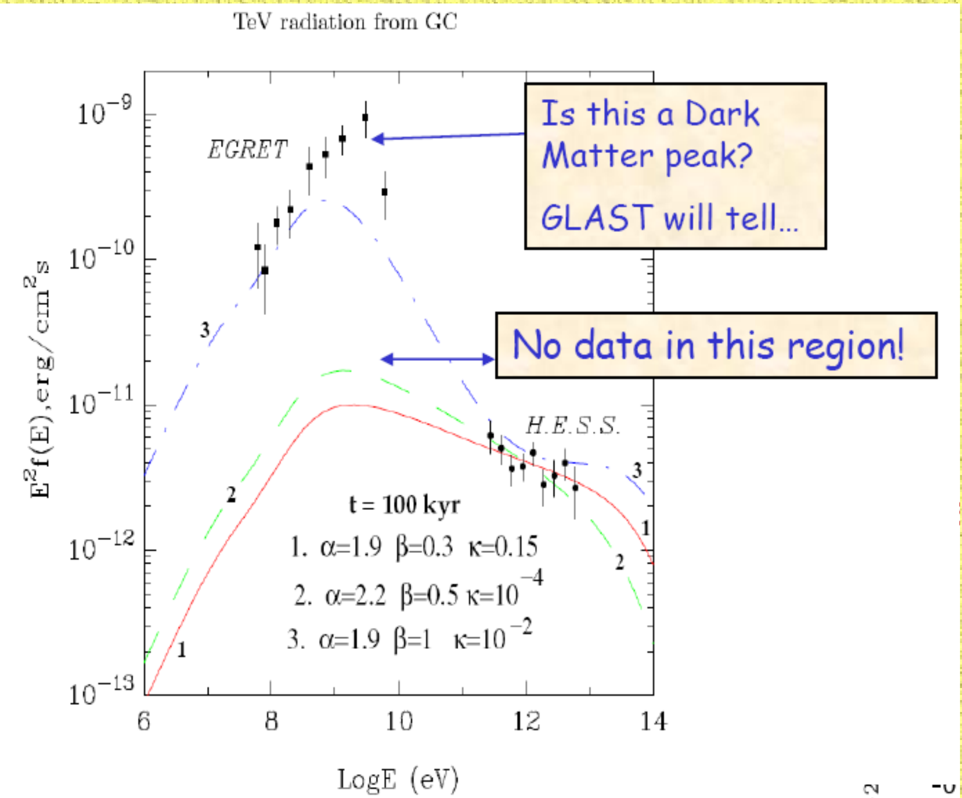
Spectral line at M_χ

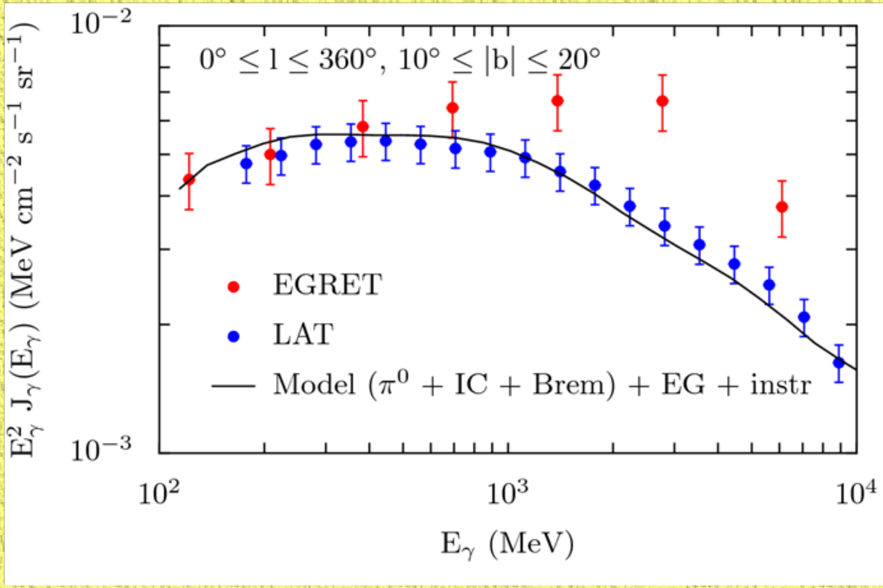
- Detection of prompt annihilation into γγ (γZ^0) would provide smoking gun for dark matter annihilation
- Requires best energy resolution
- However, annihilation fraction in the range 10^{-3}-10^{-4} (depending on the model)



Anomalous Cosmic Gamma Spectrum

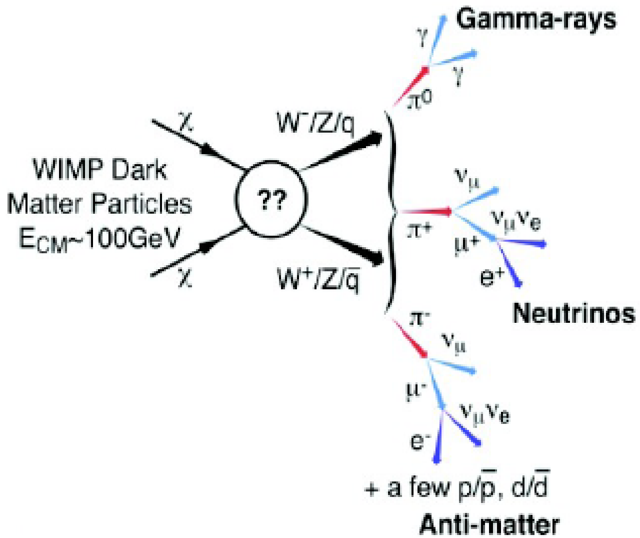
! from ERGET, *NOW* tested by Fermi





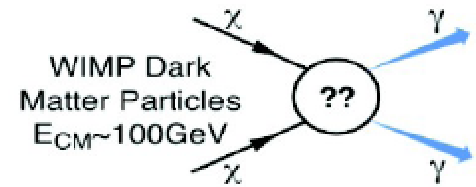
γ-rays from WIMP annihilation

Continuum spectrum with cutoff at M_χ



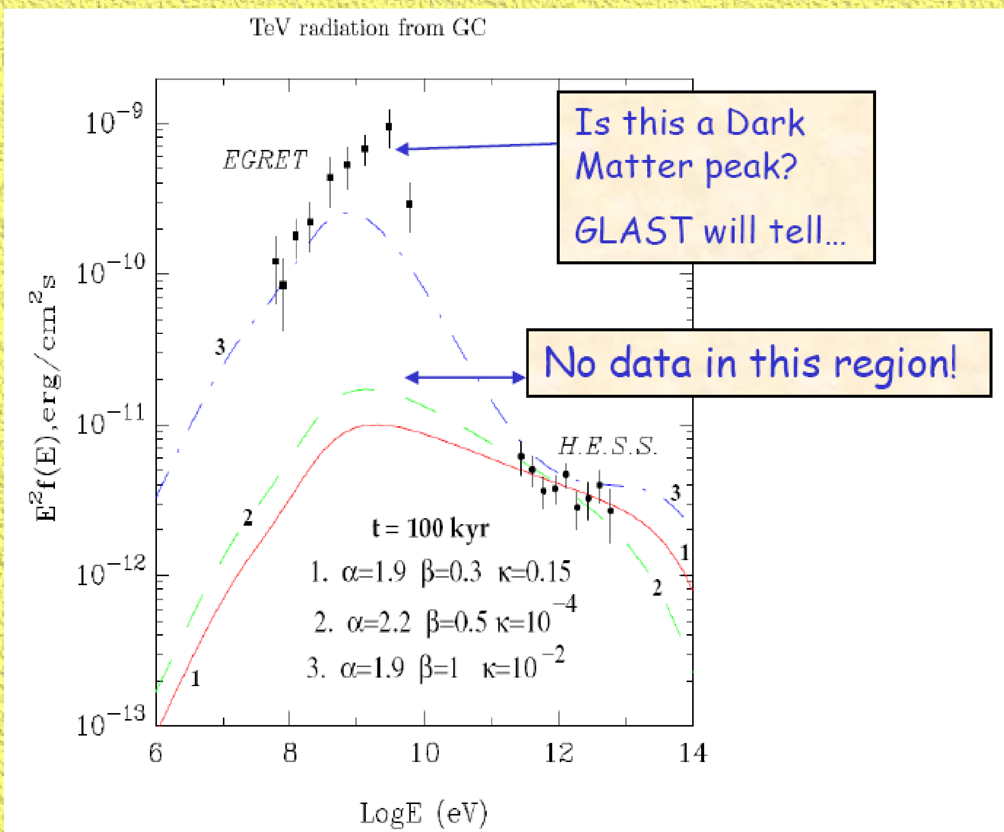
Spectral line at M_χ

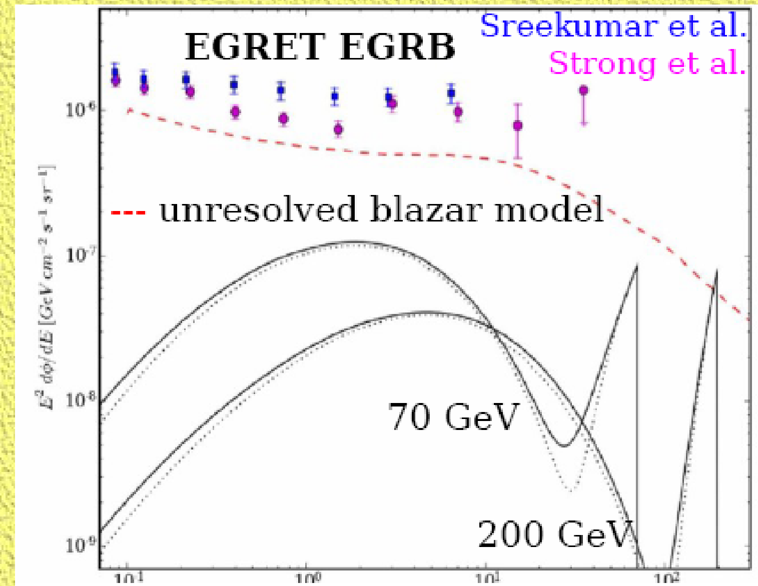
- Detection of prompt annihilation into γγ (γZ^0) would provide smoking gun for dark matter annihilation
- Requires best energy resolution
- However, annihilation fraction in the range 10^{-3}-10^{-4} (depending on the model)



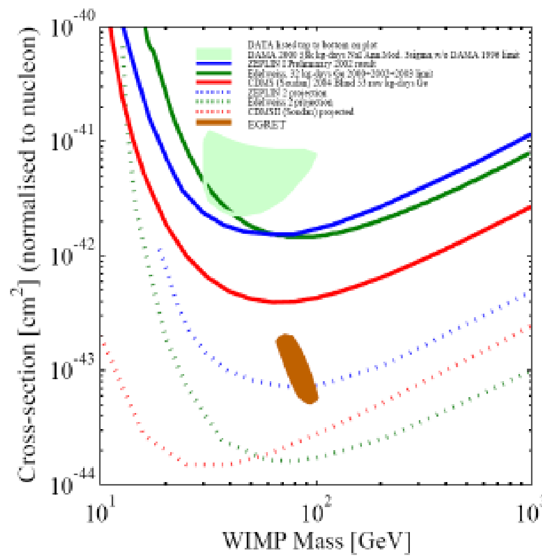
Anomalous Cosmic Gamma Spectrum

! from ERGET, soon tested by GLAST

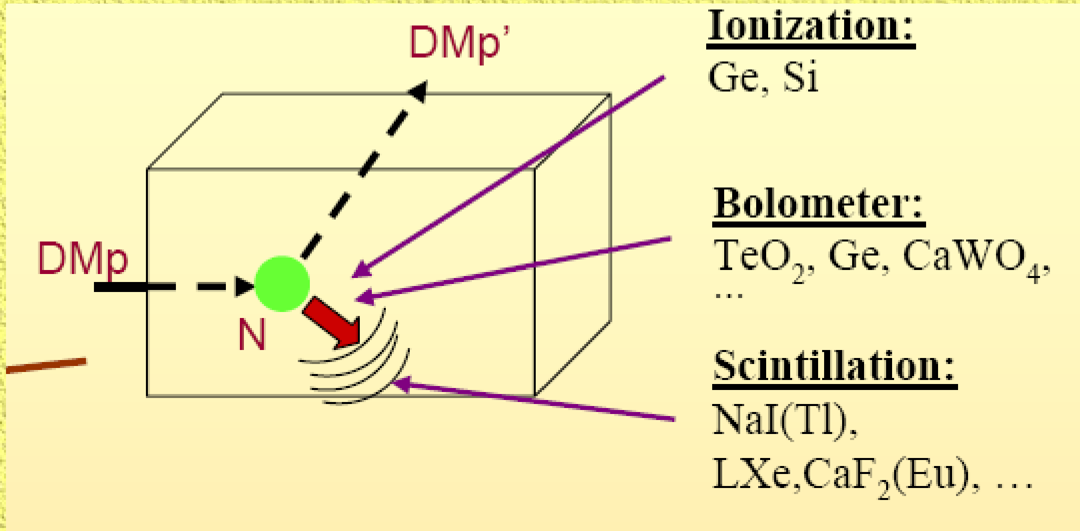


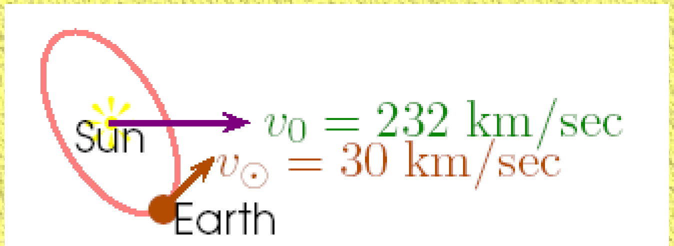


Data explained by 50-100 GeV neutralino?



WIMP Direct Detection

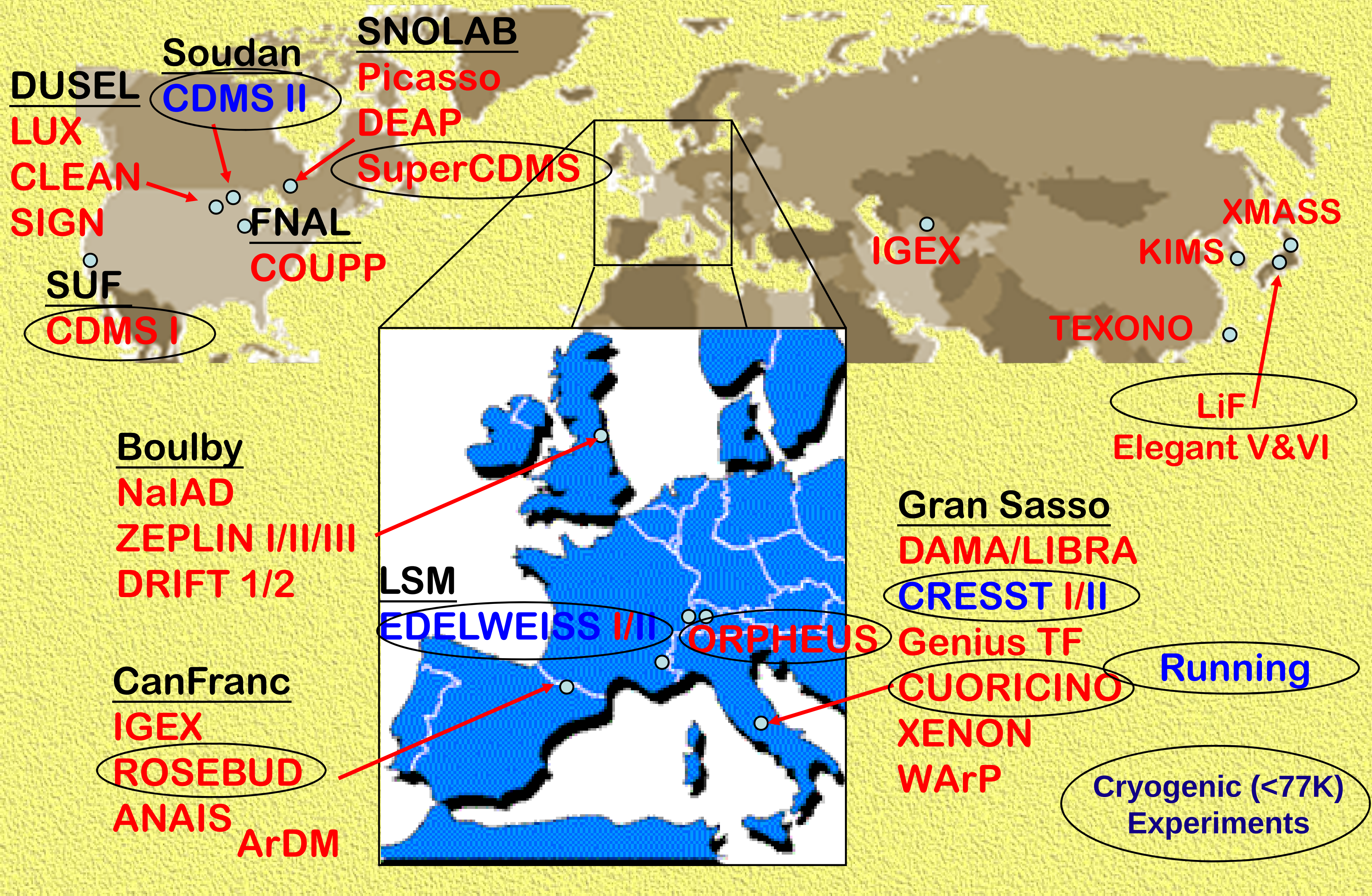




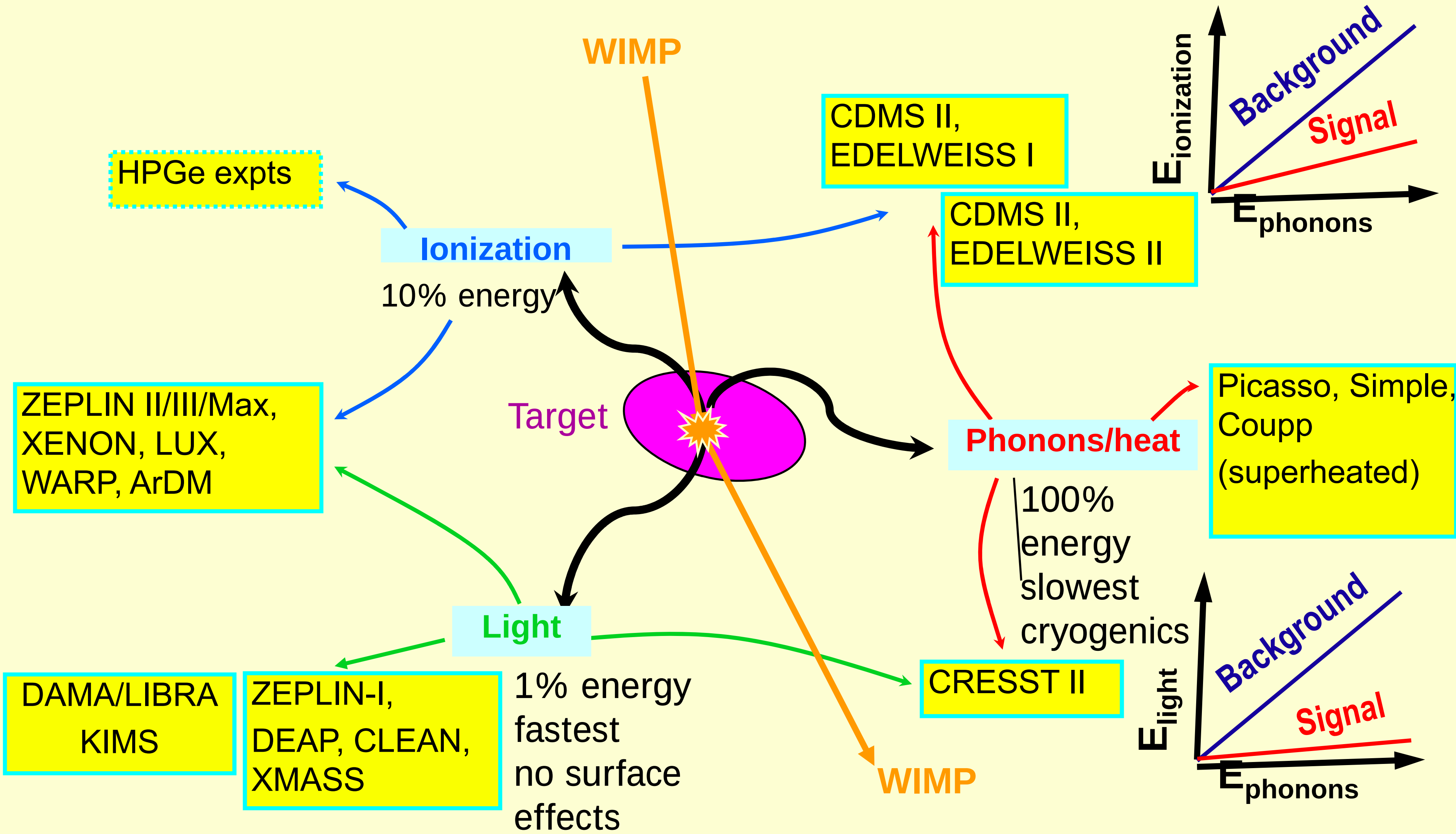
- Elastic recoil of non relativistic halo WIMPs off the nuclei
- Both Spin-Independent (~A^2) and Spin-Dependent [~(J+1/J)] Couplings
- Recoil energy of the nucleus in the keV range
- Annual modulation effect due to the rotation of the Earth around the Sun
- Directional Recoils, experimentally challenging

WIMP-detection Experiments Worldwide

(from Subject Review TAUP-07)



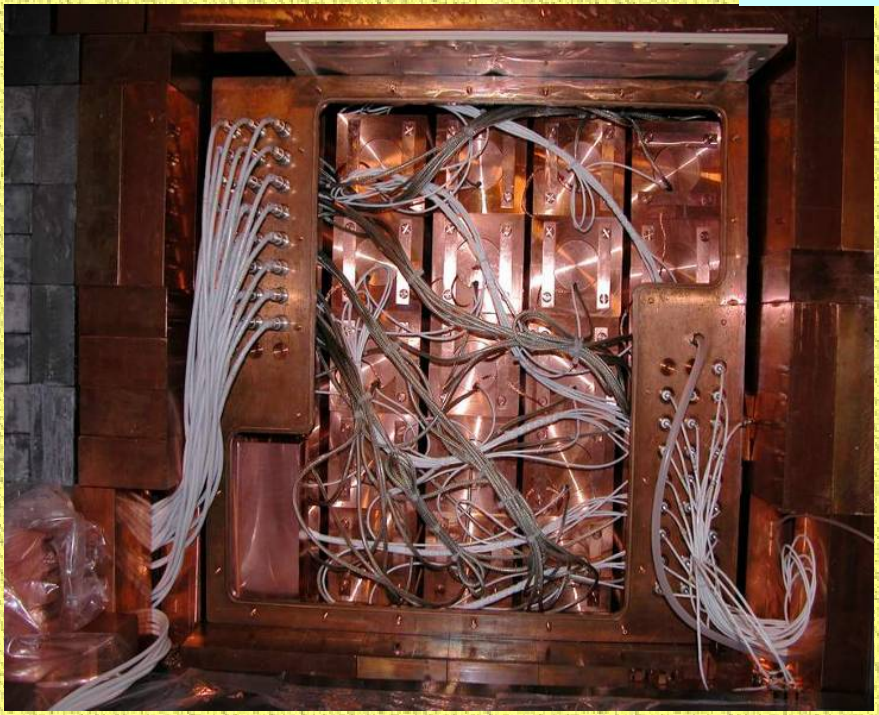
Detector Techniques - Present Focus : Nuclear Vs Electron recoils

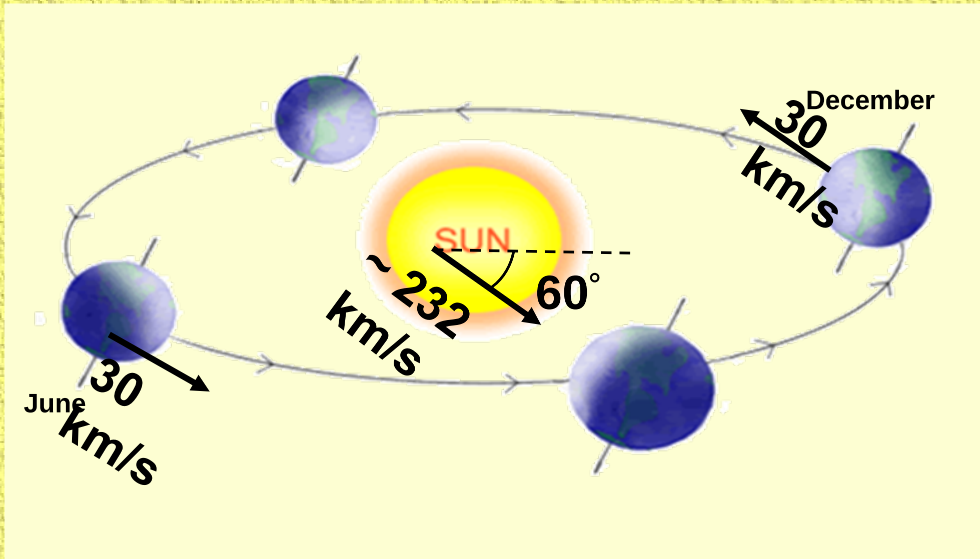


◎ **Future : Lower Threshold ; Direction Sensitive**

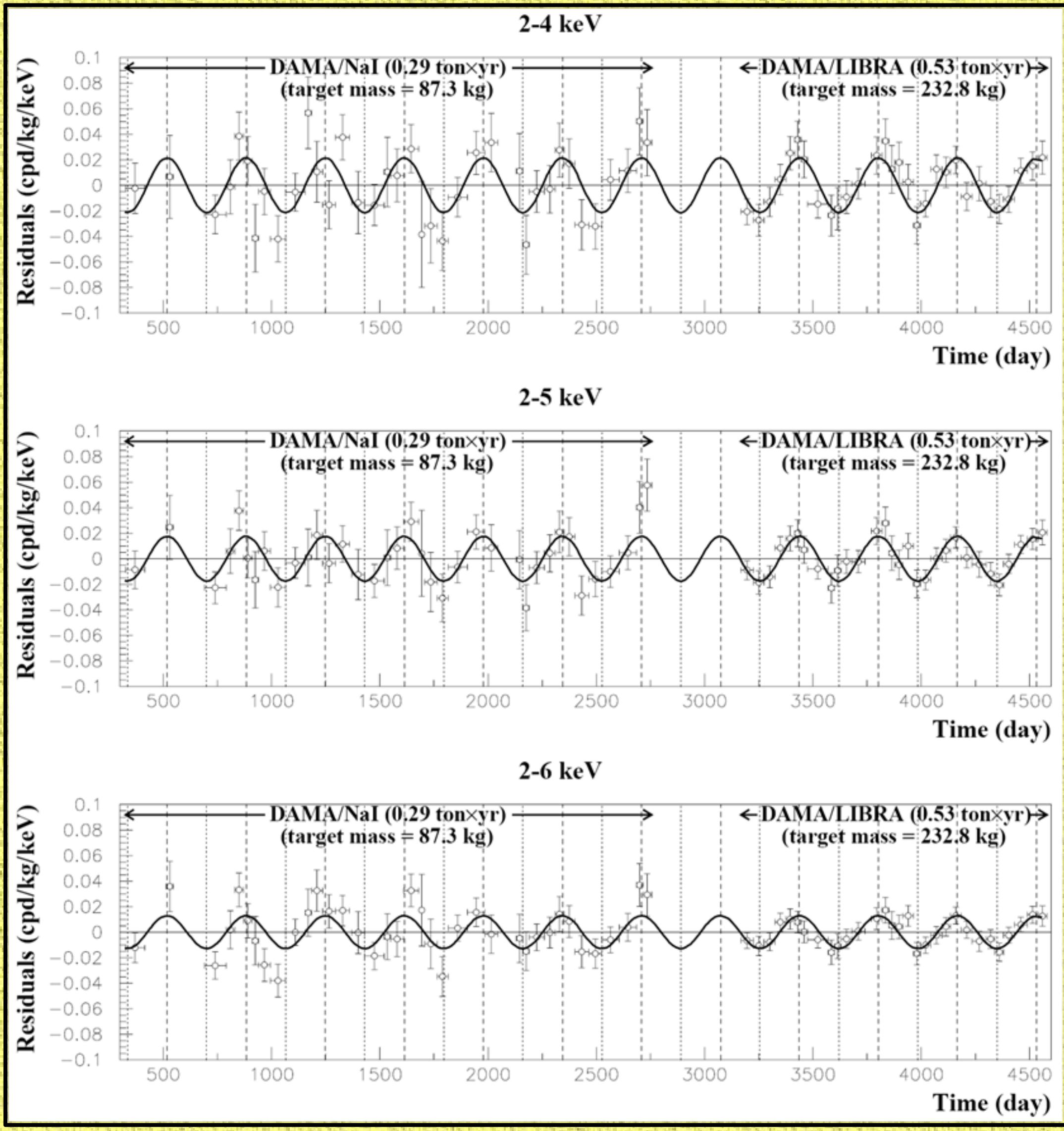
DAMA/LIBRA

- 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



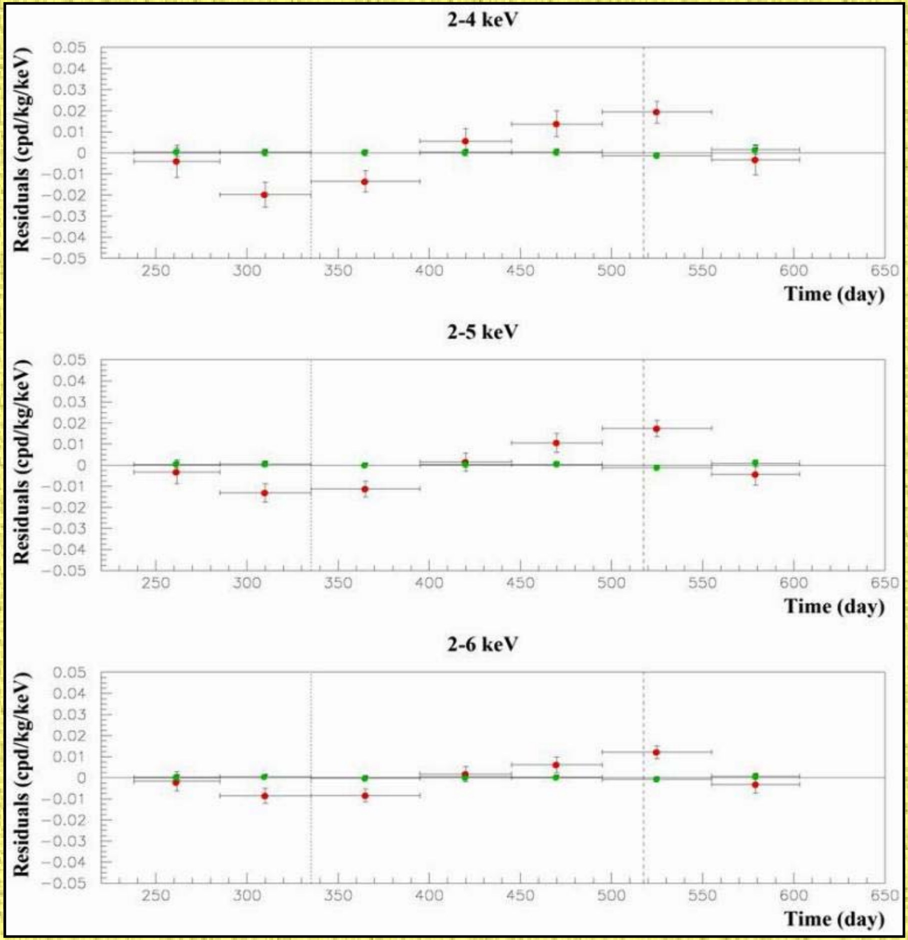


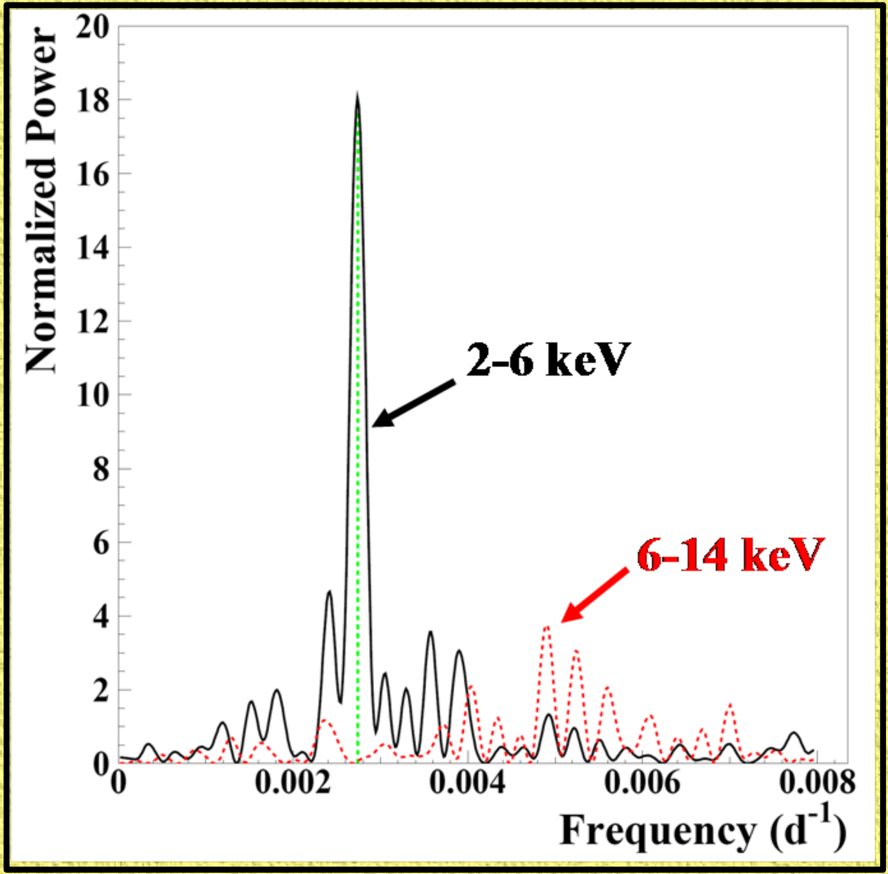
- Single Hit 2-6 keV Signal Region
- DAMA/NaI (7 years) + DAMA/LIBRA (4 years)
- Total exposure: 300555 kg×day = 0.82 ton×yr



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

Single-Hit Power Spectrum

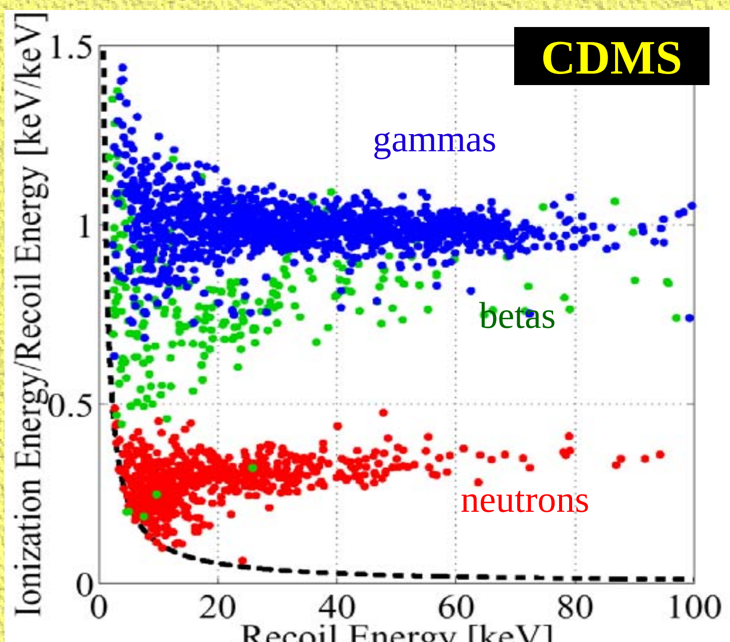


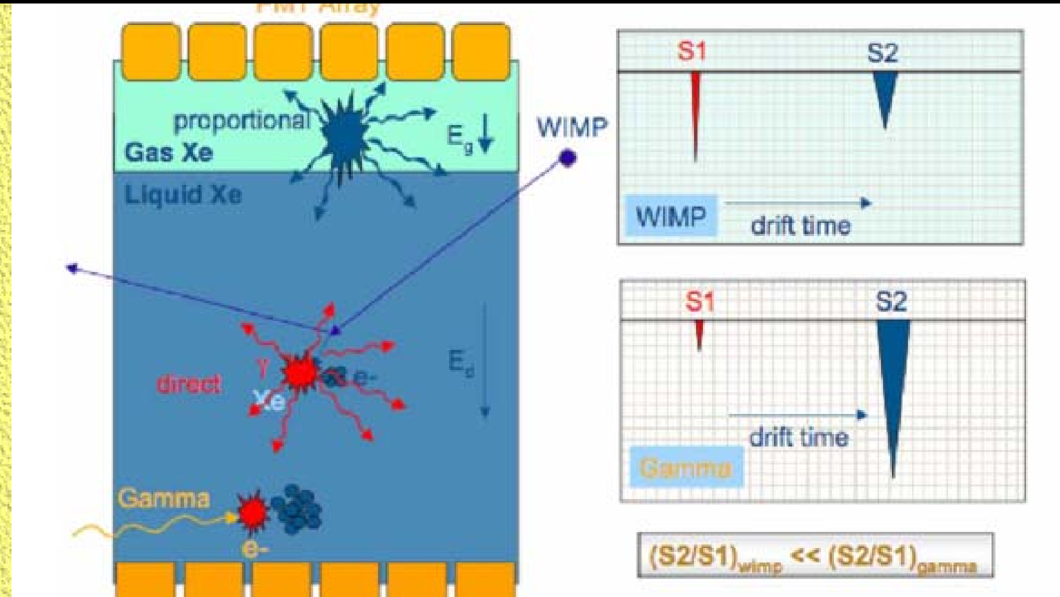


* **No Modulation for multiple hits at 2-6 keV**
* **No Modulation for single hit above 6 keV**

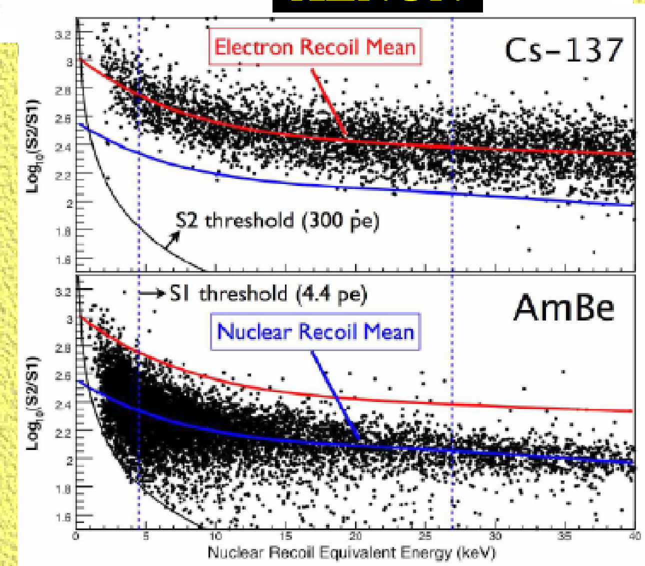
Sensitive Techniques: Phonon+Ionization & Dual Phase Xenon

⇨ Nuclear Vs electron recoils differentiation



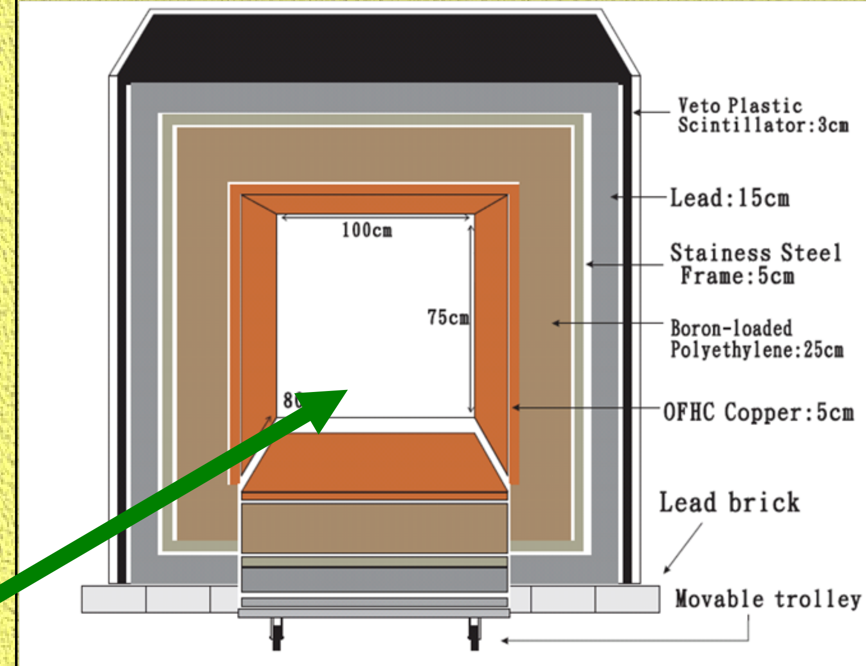


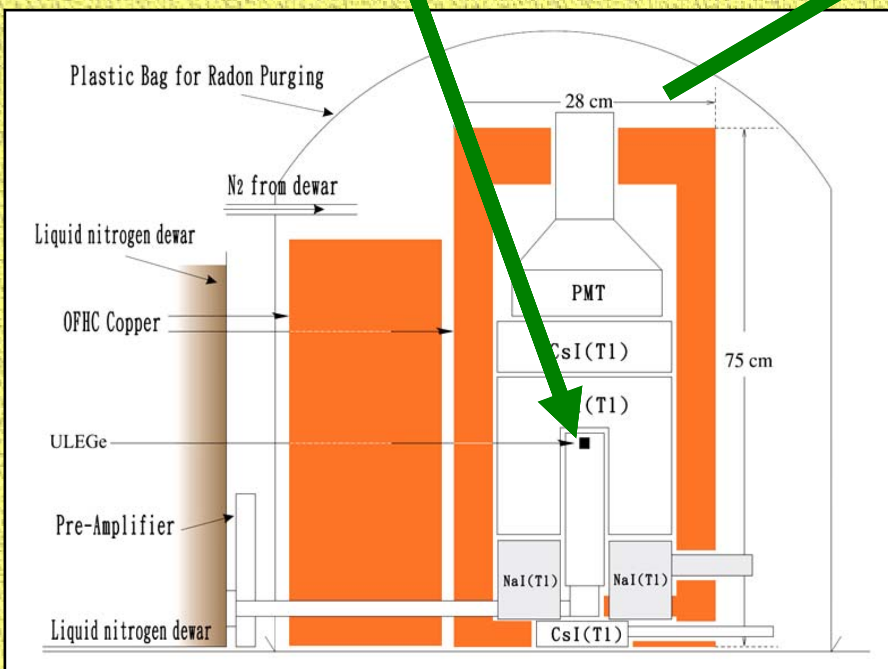
XENON



TEXONO Detector & Shieldings

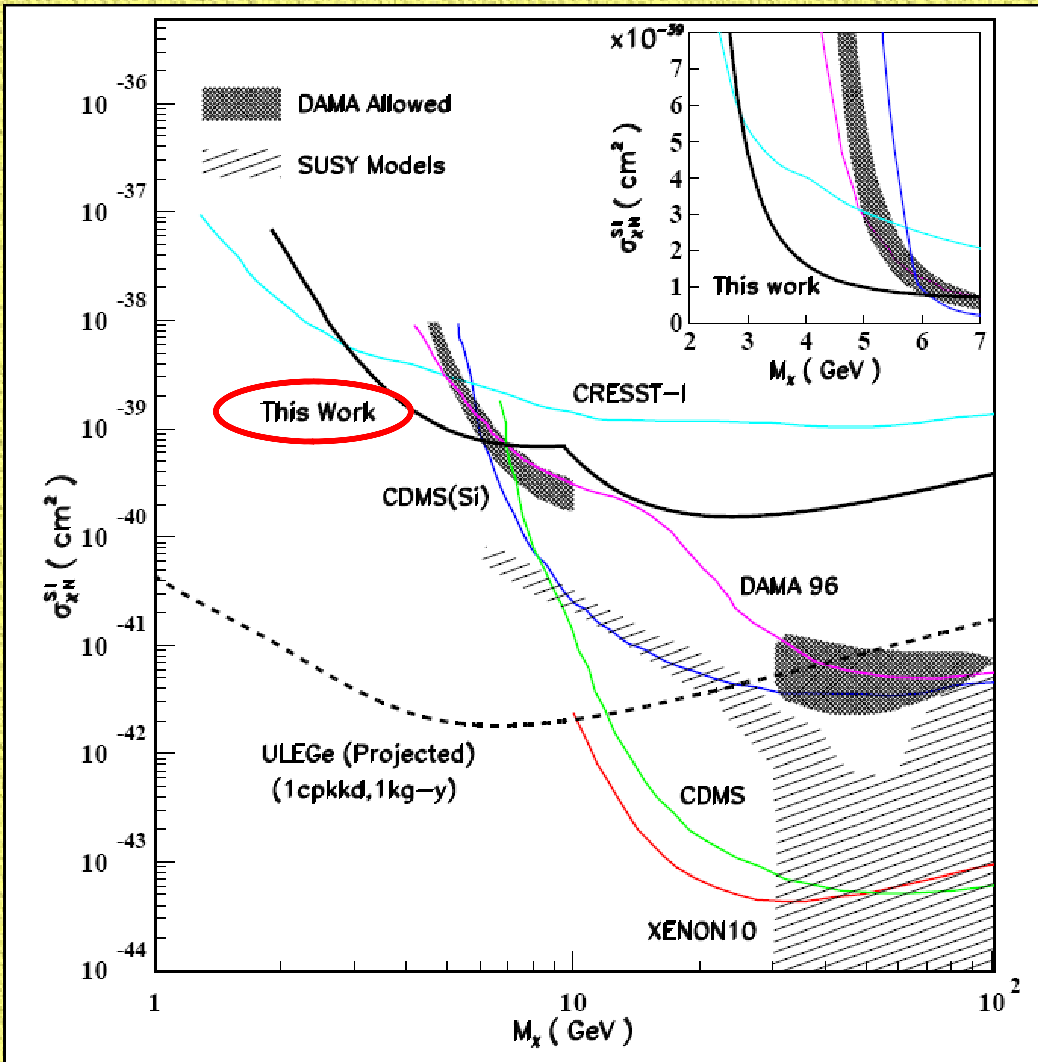
4X5g ULEGe





- *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.**

Exclusion Plot : Spin-Independent Couplings

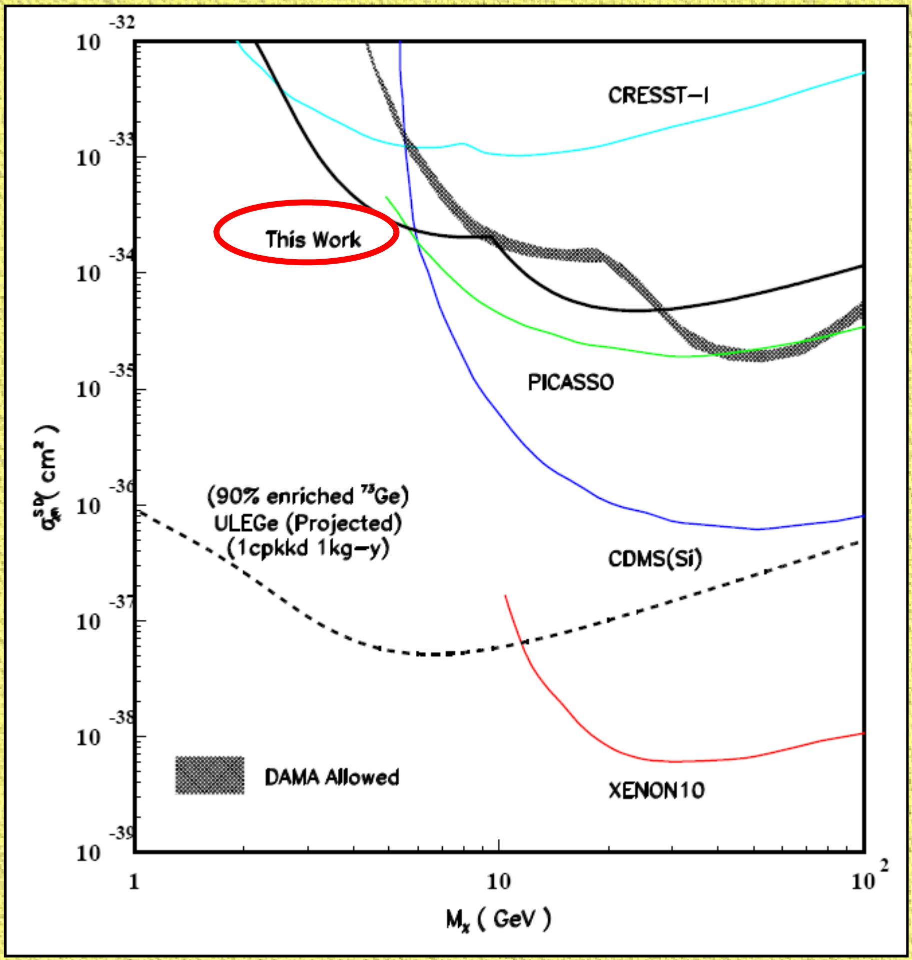


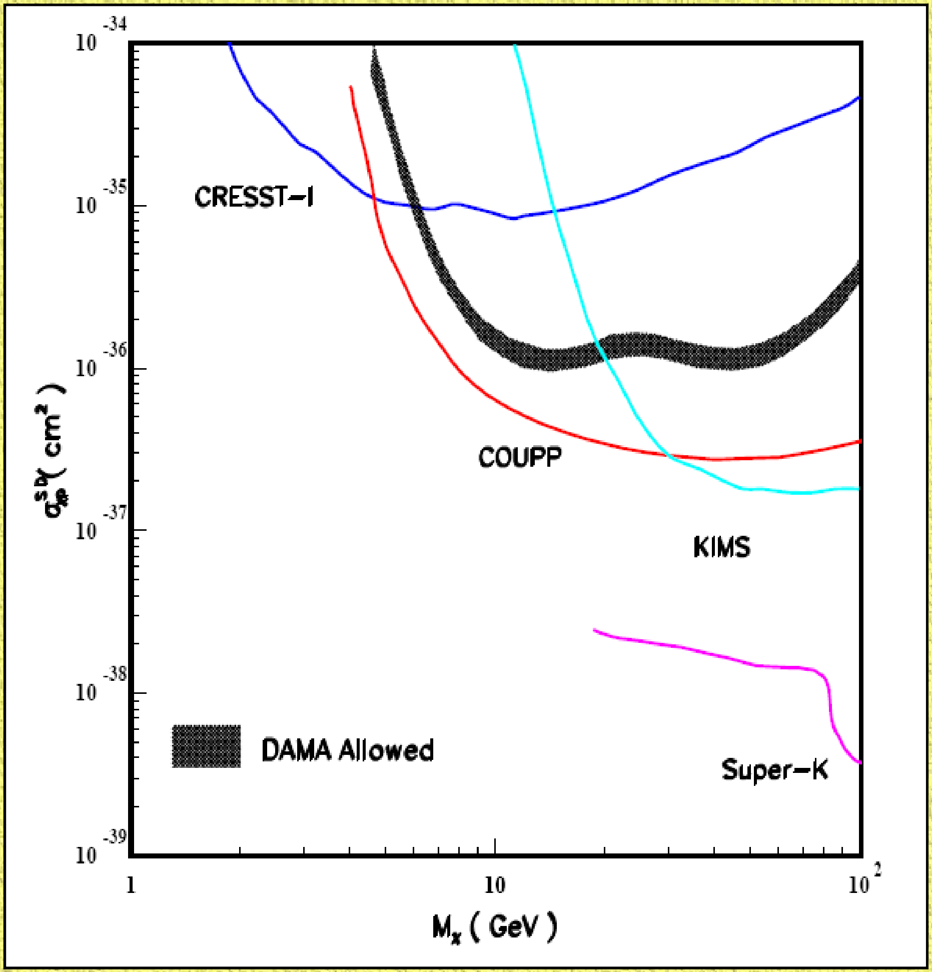
TEXONO : 20 g ULEGe at 220 eV threshold ⇒ low WIMP masses *[PRD 2009]*

[Lin ST's talk]

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

Exclusion Plot : Spin-Dependent Couplings

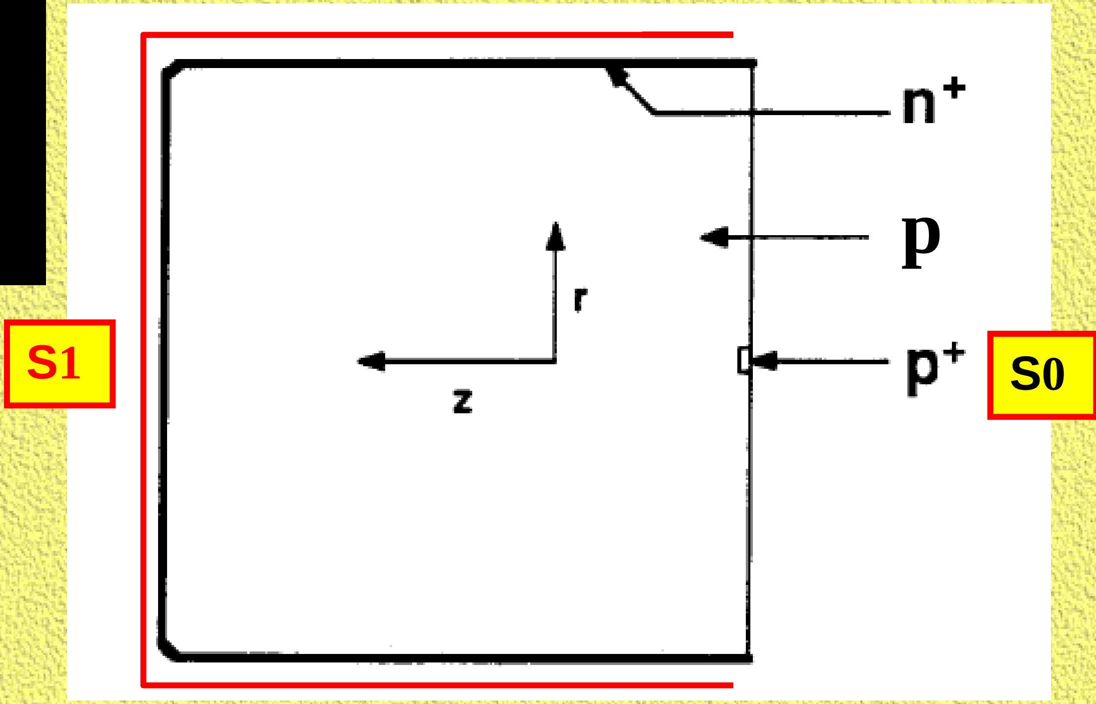




To Reconcile DAMA Results:

- ? Do we understand of WIMP physics and astrophysics properties (mass, local density distribution, local velocity distributions…)
- ? Do we understand how WIMP interacts with matter (e.g. χ-e)
- ? Do we understand our detector response (e.g. Quenching Factor in crystal lattice…)

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
- 900-g detector under construction

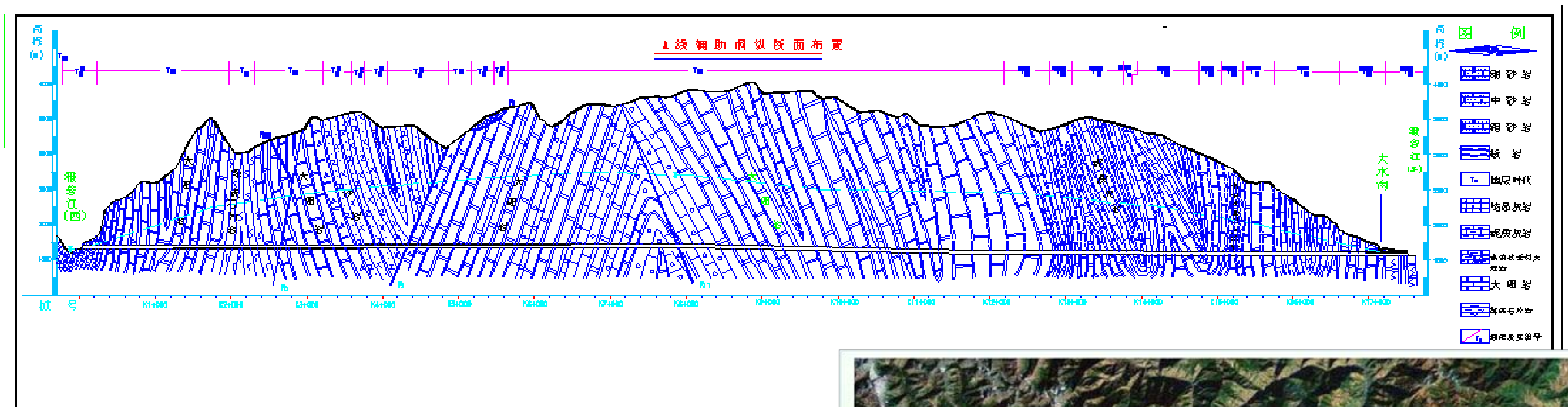
New Opportunities : Excellent Candidate Site for Underground Lab. at 四川錦屏, China

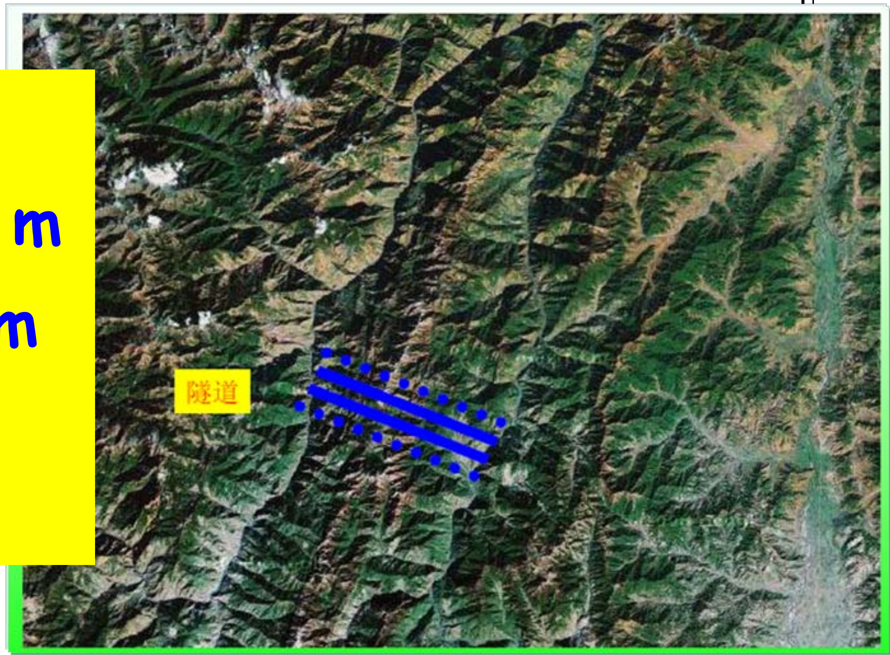
穿越锦屏山的锦屏二级水电站引水隧洞的最大埋深为2525米，四条隧洞的总长度超过了70公里，组成了世界规模最大的发电引水隧洞群。图为一号隧洞的TBM掘进机作业场景。（刘渝 喻安谋摄影报道）

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

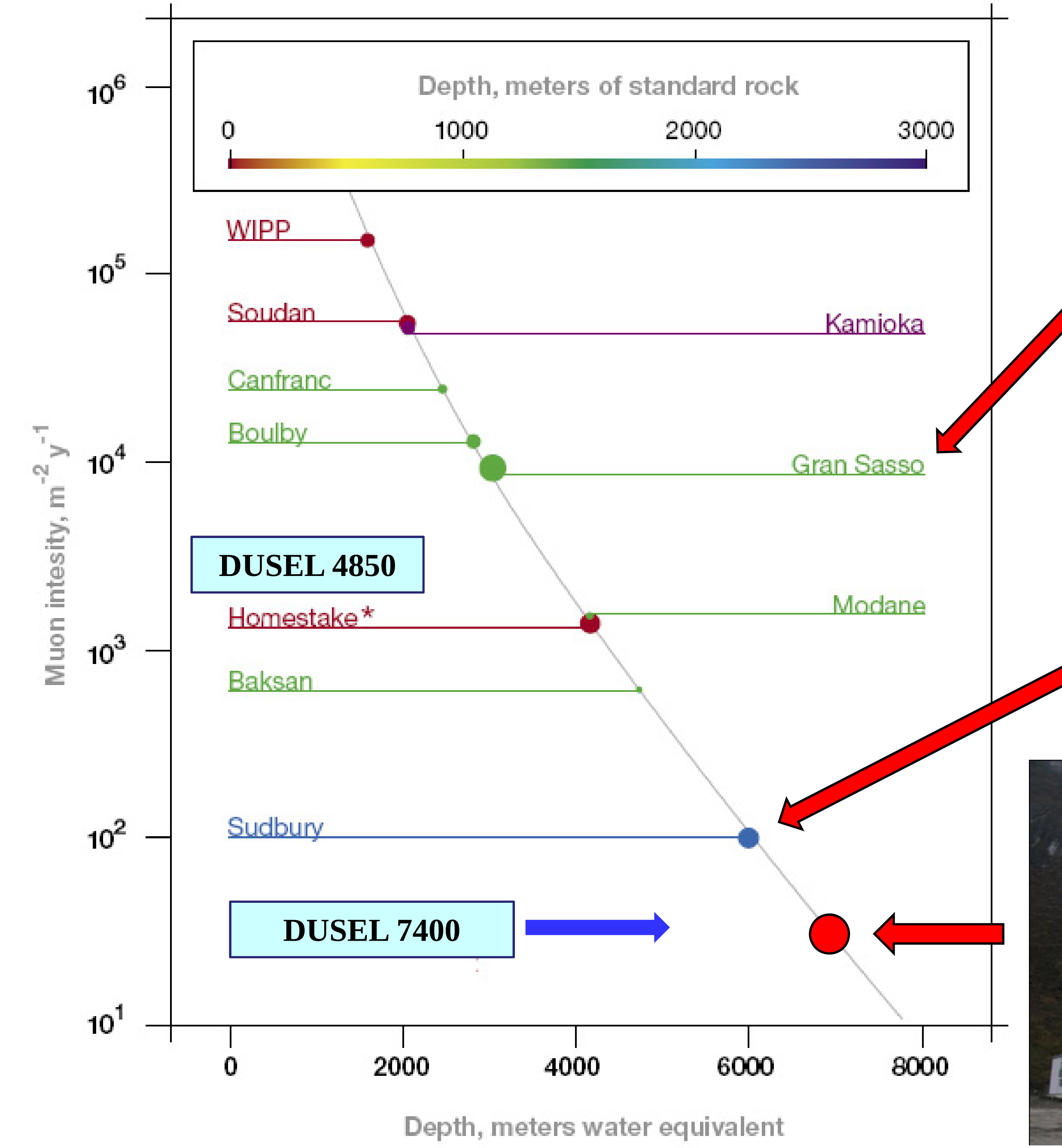
锦屏山隧道
Mt. Jin-Ping Tunnel

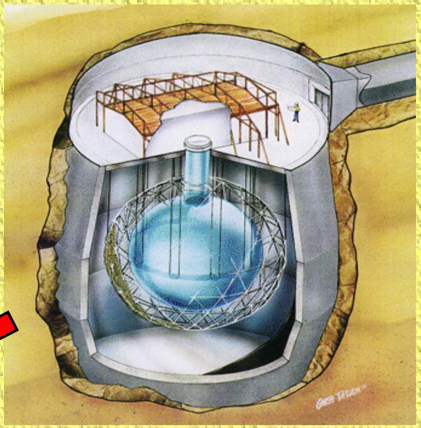
- MoU signed May 2009
- Excavation of 1st cavern begins 2009
- Operating ULEGe 2010.





- Tallest Peak 4193 m
- Max. Rock Overburden: 2375 m
- Road Tunnel Distance: 17.5 km
- Fraction of tunnel with >1500 Rock Overburden: >70%


Depth, meters of standard rock
0
1000
2000
3000
WIPP
Soudan
Kamioka
Canfranc
Boulby
Gran Sasso
DUSEL 4850
Homestake*
Modane
Baksan
Sudbury
DUSEL 7400
10^6
10^5
10^4
10^3
10^2
10^1
Muon intesity, $m^{-2}\ y^{-1}$
0
2000
4000
6000
8000
Depth, meters water equivalent




四川錦屏

Axions

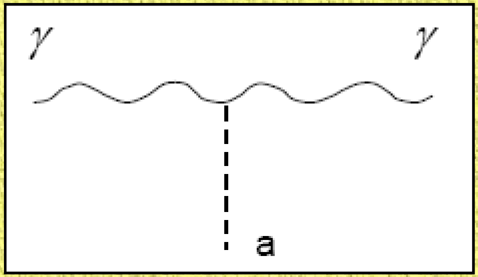
- **Invented to Solve "Strong CP Problem"**
- **Produced via QCD Phase-Transition in early Universe: i.e. Cold (non-relativistic)**
- **Couples to Photons & Electrons**

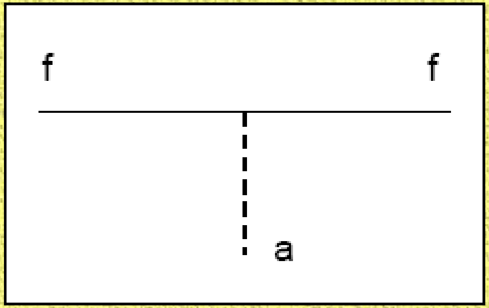
The Strong CP Problem

$$L_{QCD} = \ \dots + \ \theta \frac{g^2}{32\pi^2} G^a{}_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Because the strong interactions conserve P and CP, $\theta \leq 10^{-10}$. {neutron dipole moments}

The Standard Model does not provide a reason for θ to be so tiny,





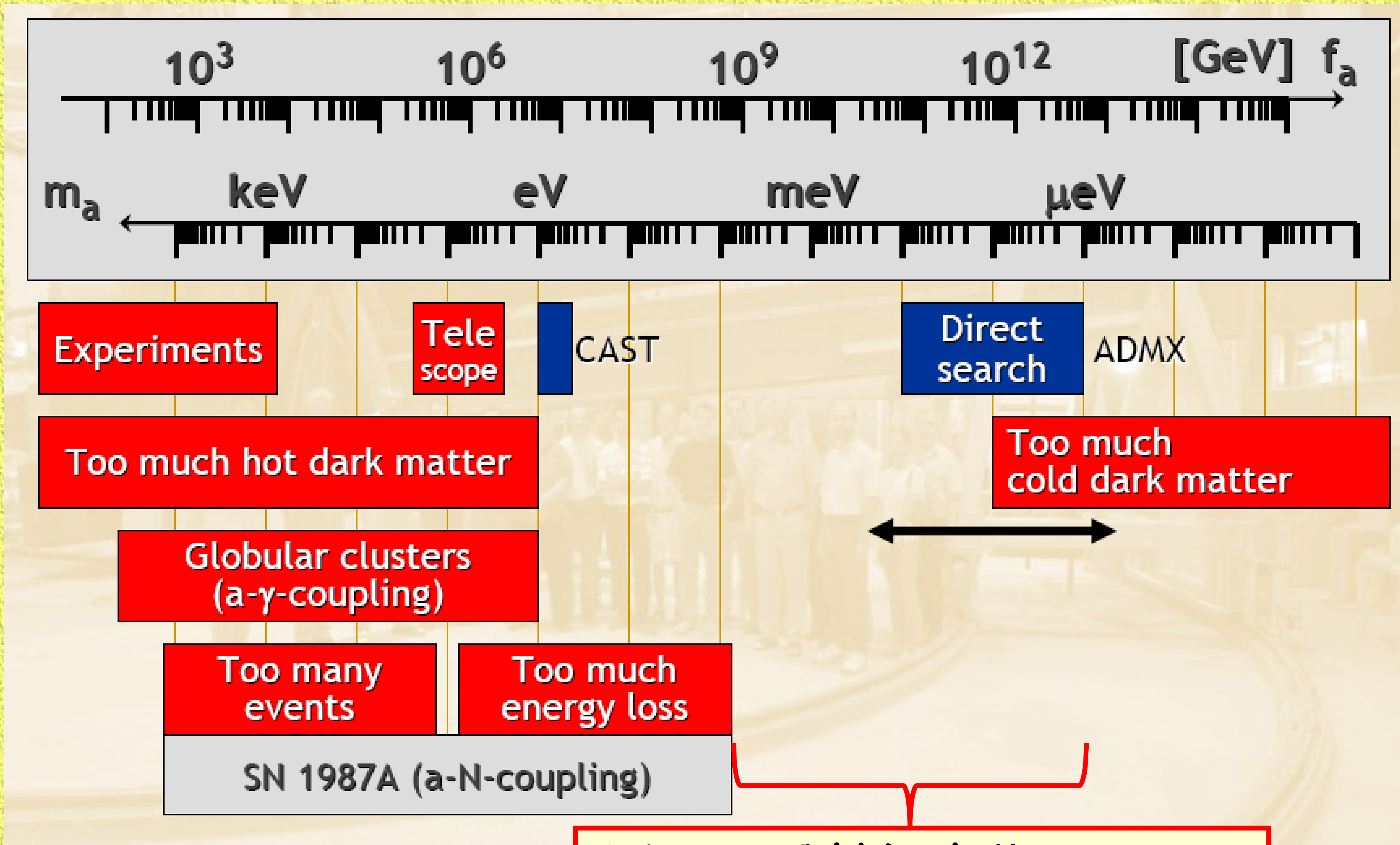
Assume $U_{PQ}(1)$ symmetry

$$L = \ \dots + \frac{a}{f_a} \frac{g^2}{32\pi^2} G^a{}_{\mu\nu} \tilde{G}^{a\mu\nu} + \frac{1}{2} \partial_\mu a \, \partial^\mu a + \dots$$

$\theta = \frac{a}{f_a}$ → **0** $\Rightarrow$ **light neutral pseudoscalar**

$$m_a \sim \ \text{eV} \ \frac{10^6 \ \text{GeV}}{f_a}$$

Laboratory & Astrophysics Bounds on Axions

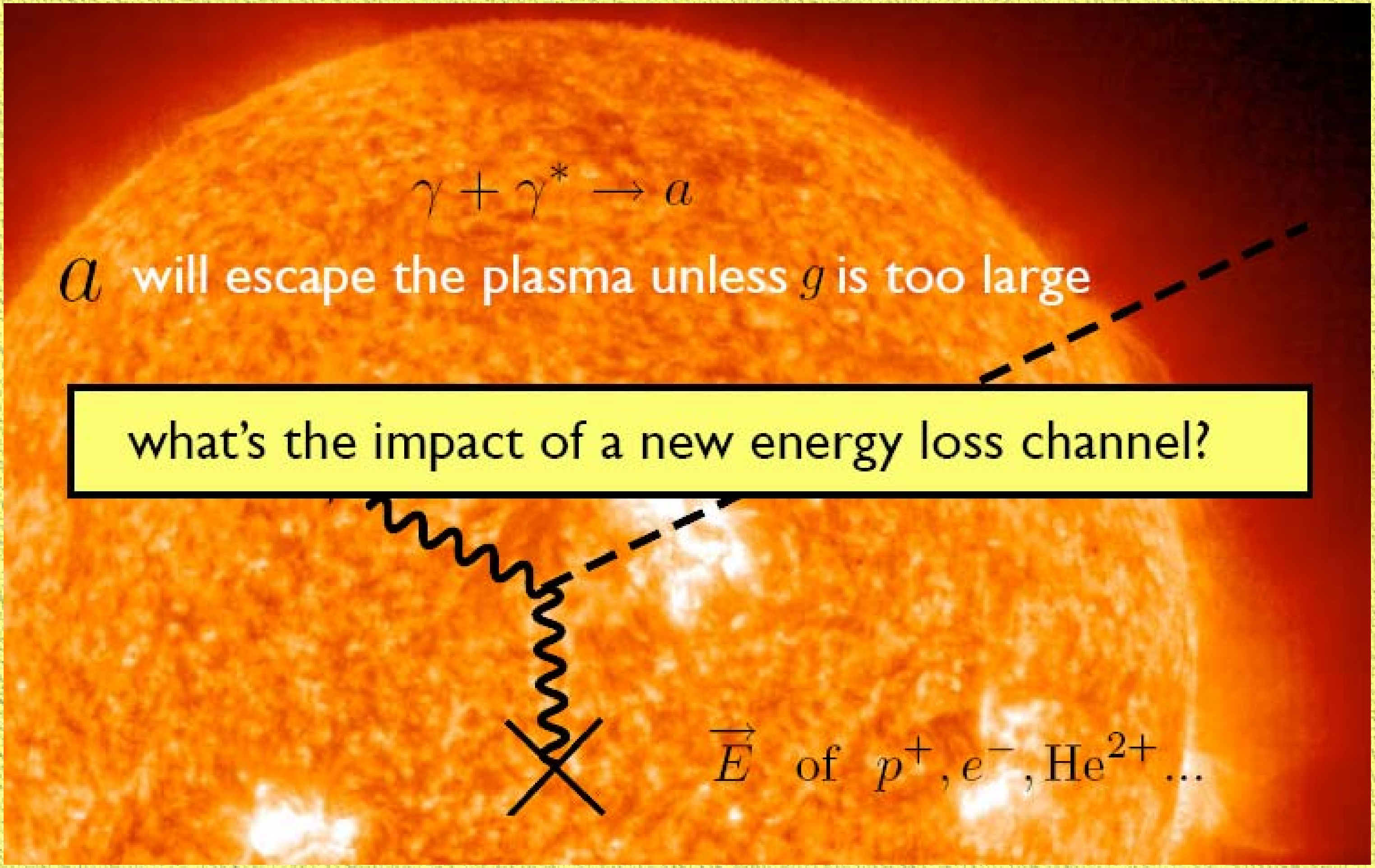


Axions as Cold Dark Matter :

Allowed Mass Range

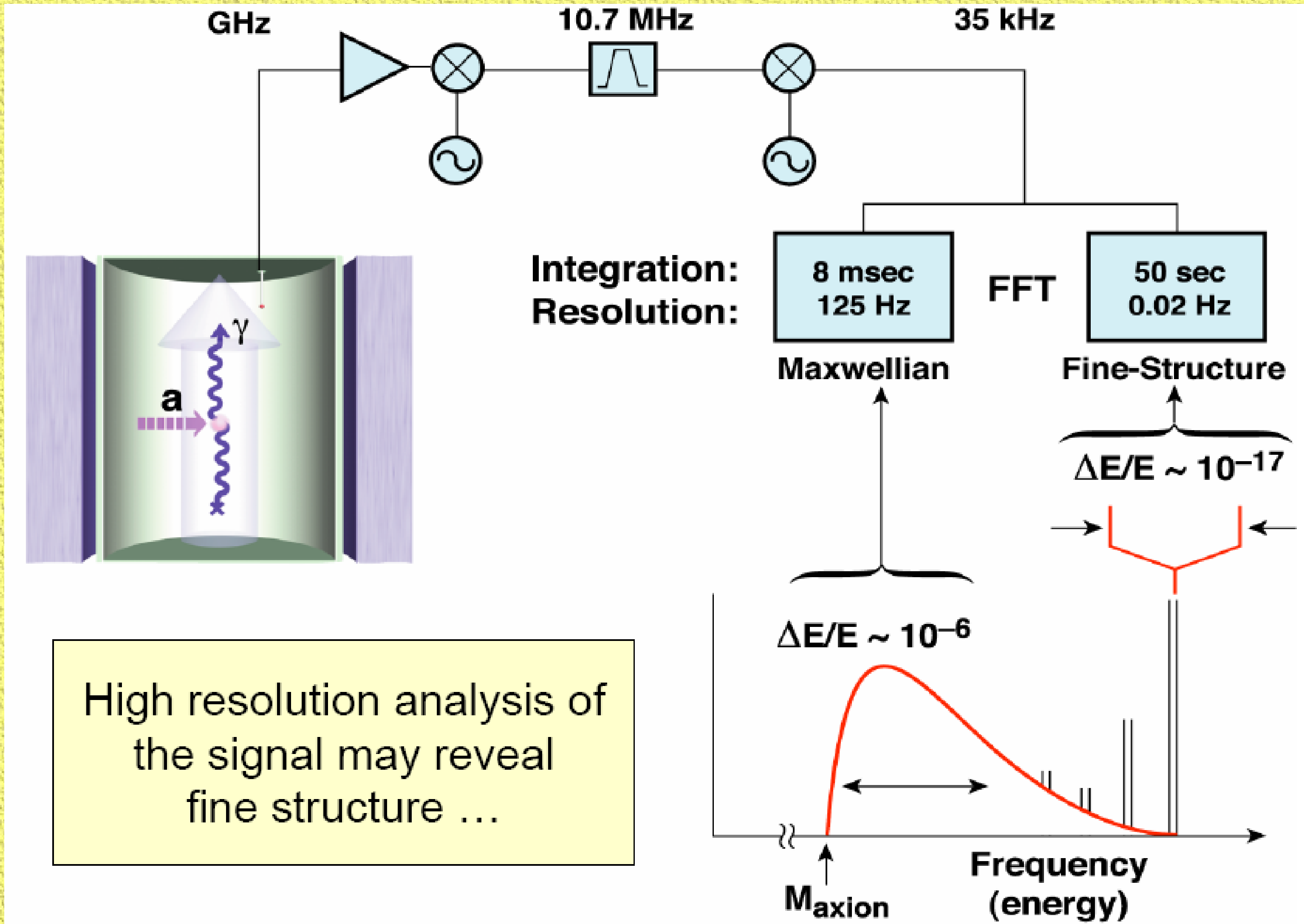
~ 10^{-2} – 10^{-6} eV

Essence of Astrophysics Bounds



- **Constraints from Stellar Cooling at Sun (main sequence), supernovae, white dwarf, global clusters, red giants**

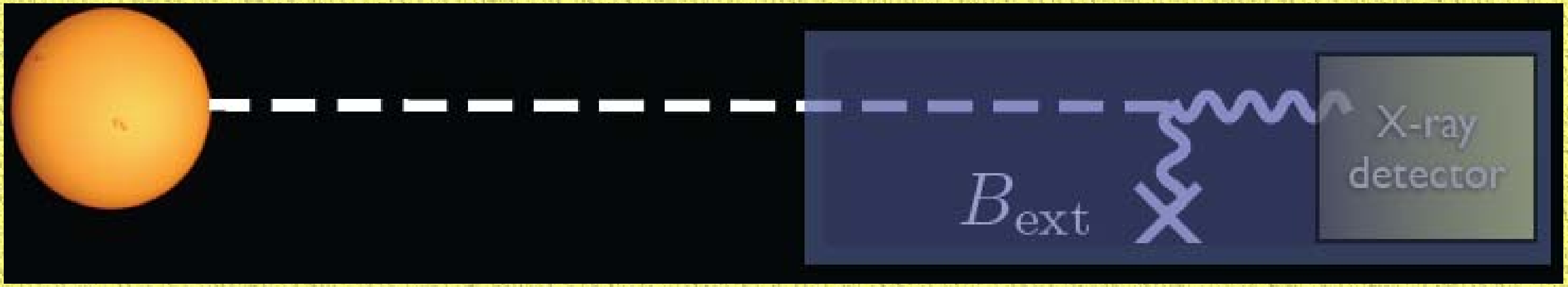
Microwave Cavity Experiments (e.g. ADMX)

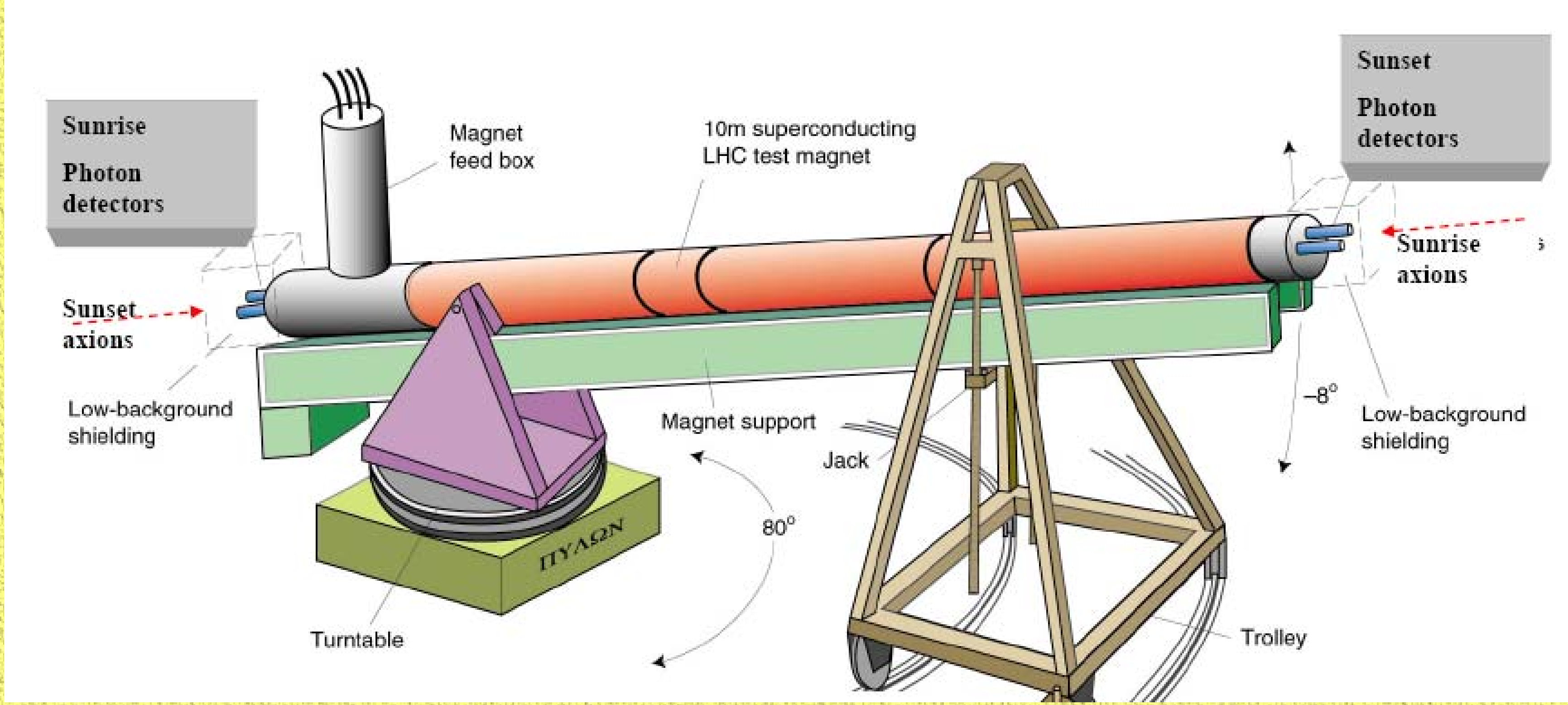


High resolution analysis of the signal may reveal fine structure …

Excellent Analyzing Power but Limited Bandwidth

Solar Axion Experiments (e.g. CAST)

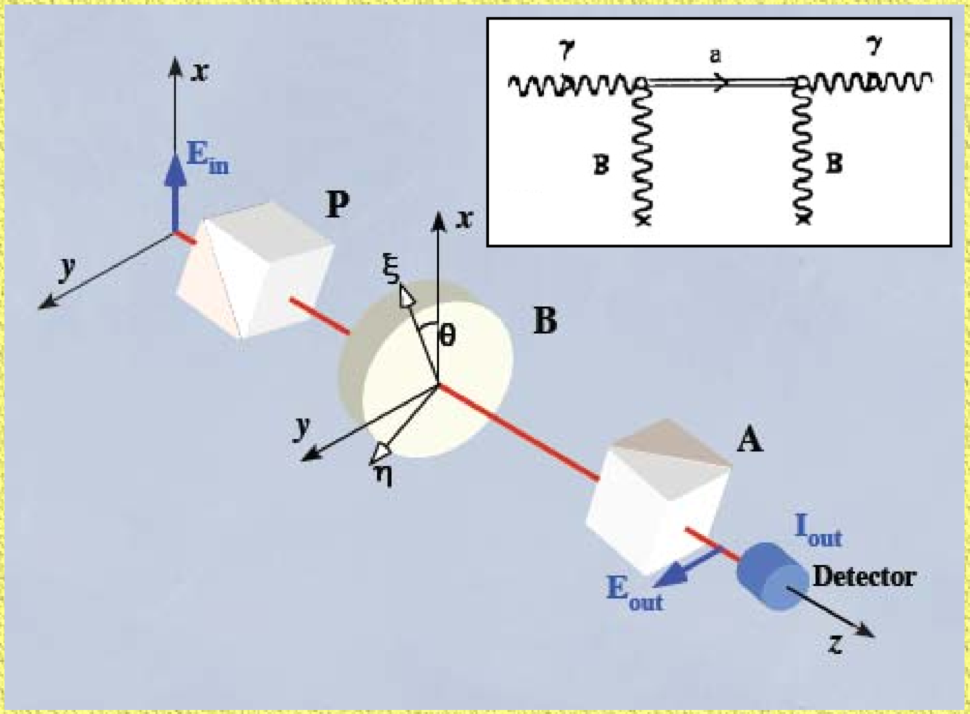


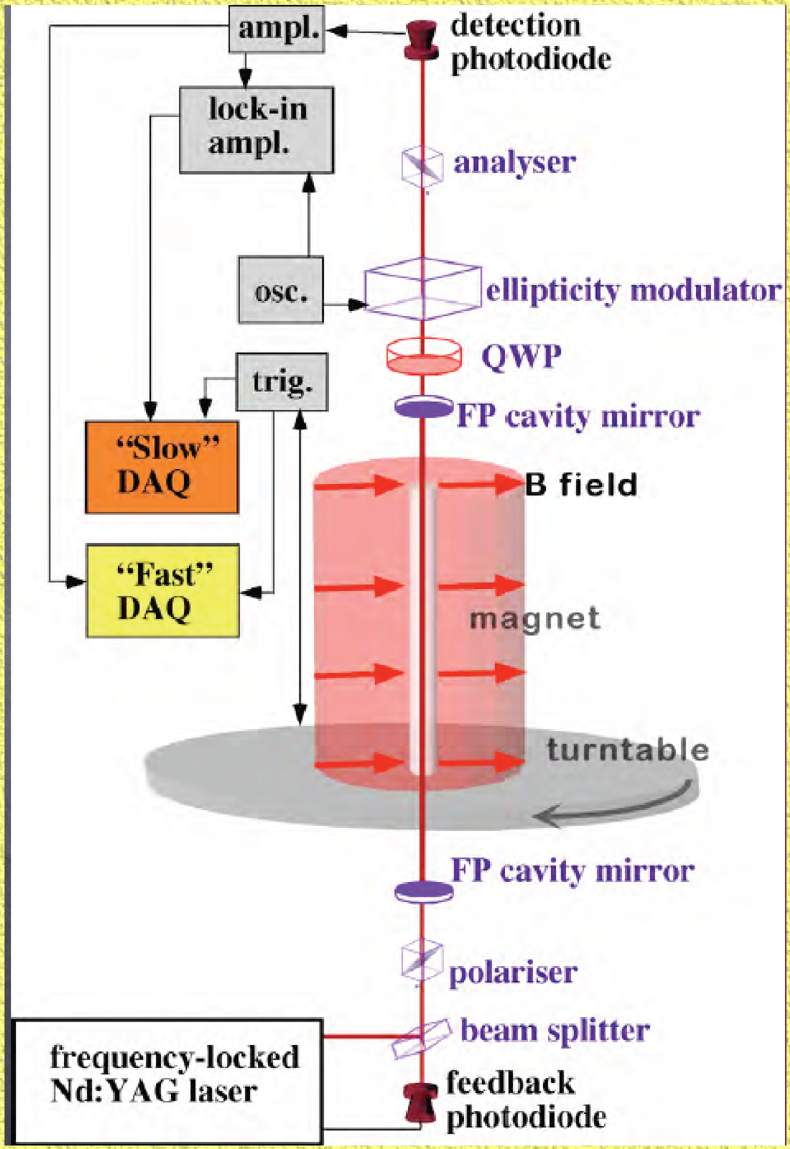


Polarization Rotation Experiments (e.g. PVLAS)

Primakoff effect reduces parallel component, perpendicular component unchanged

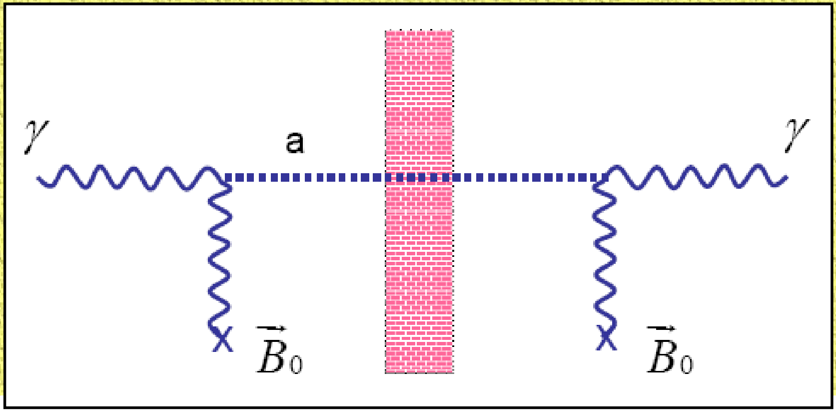
- Rotates the plane of polarization

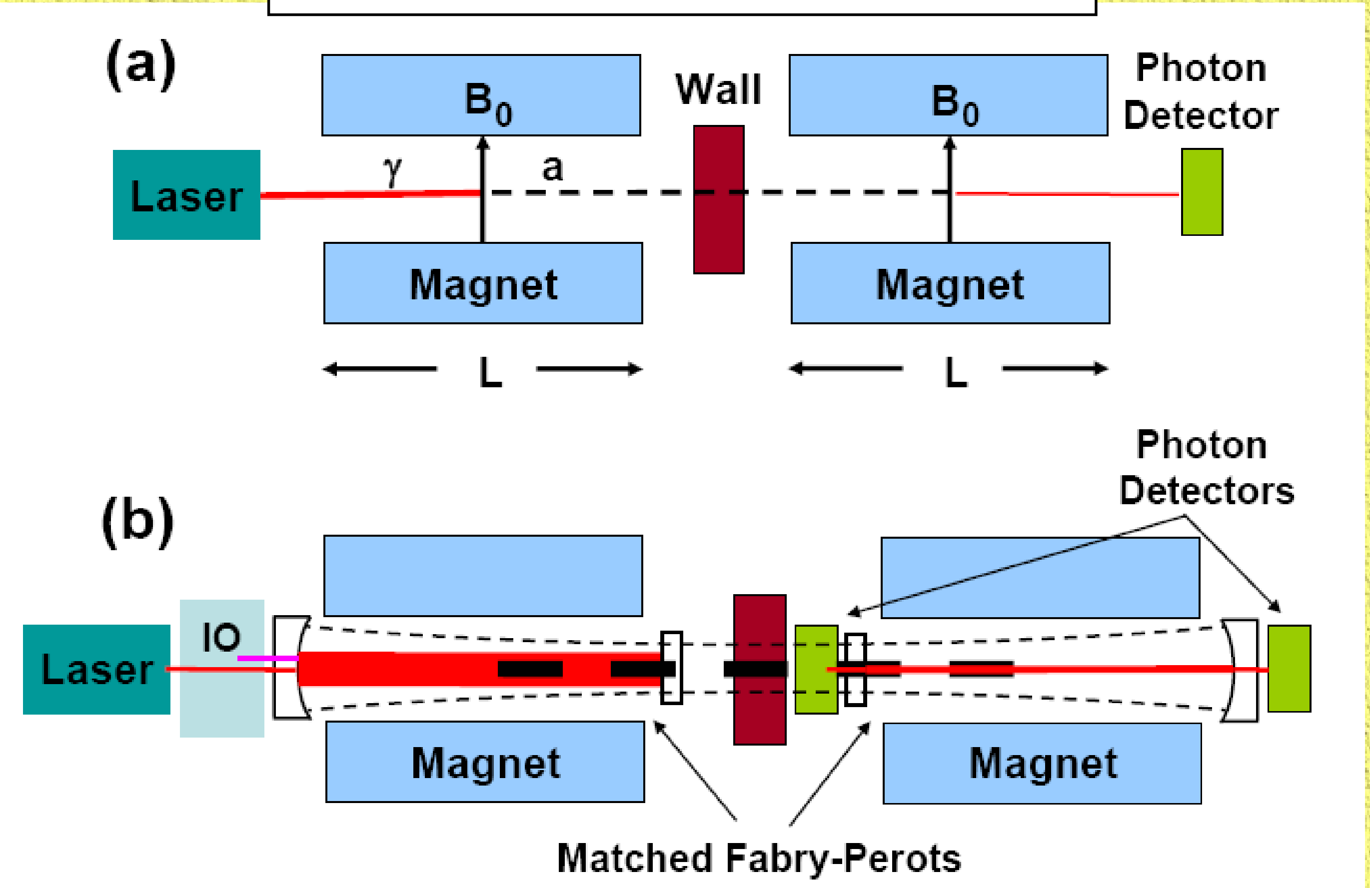




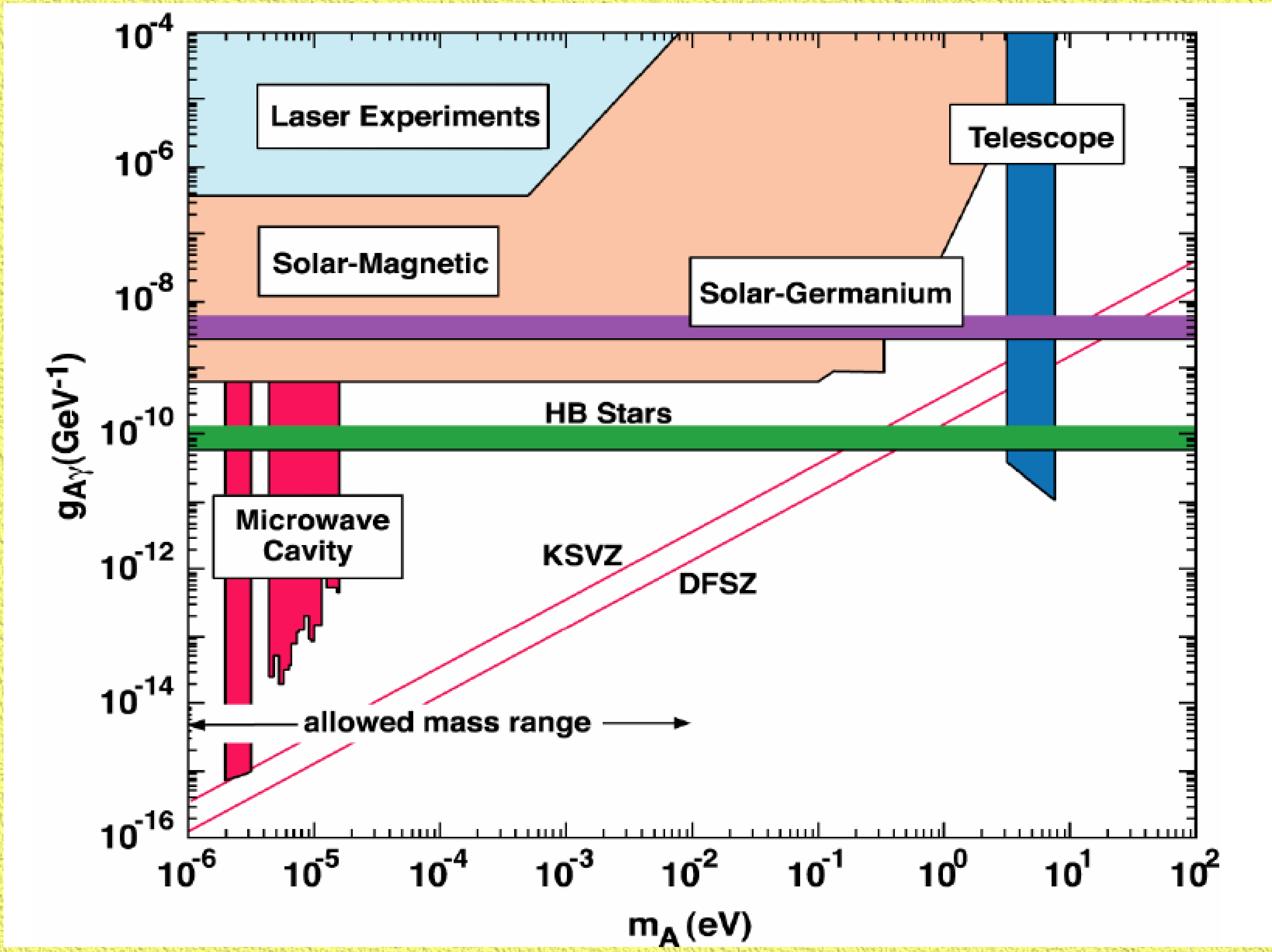
Earlier anomalous signals disappear !!

Axion-Photon Conversion Experiments

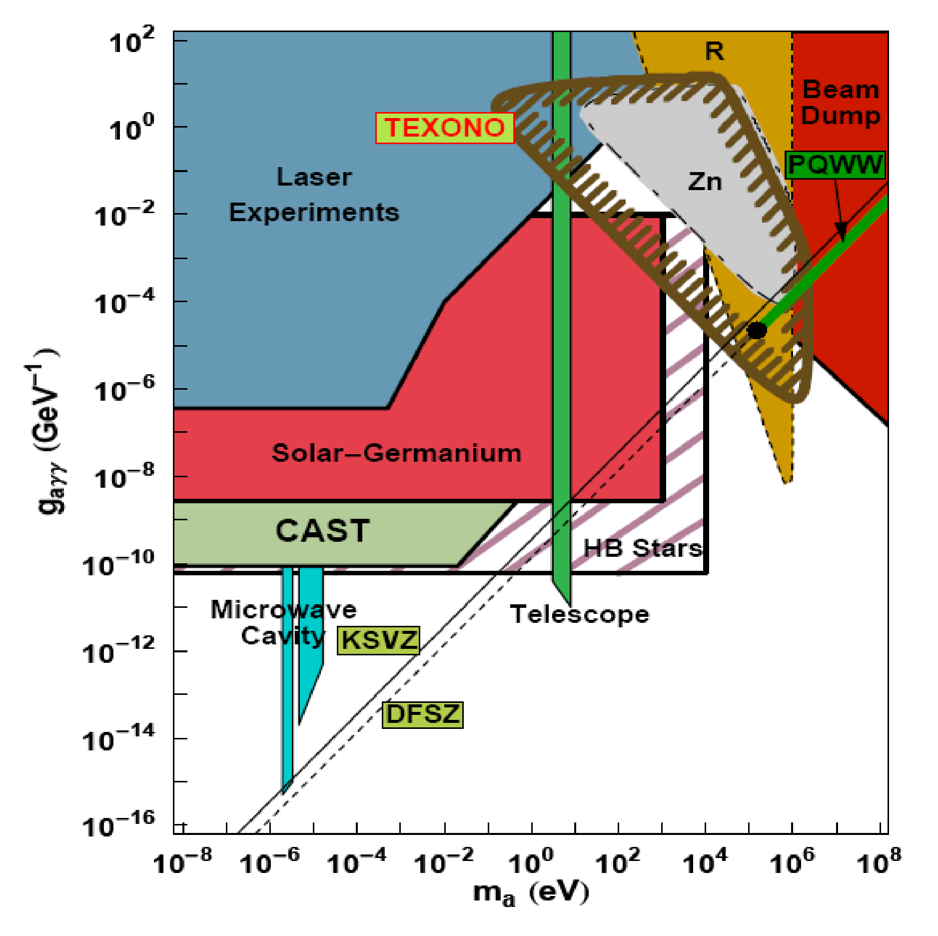


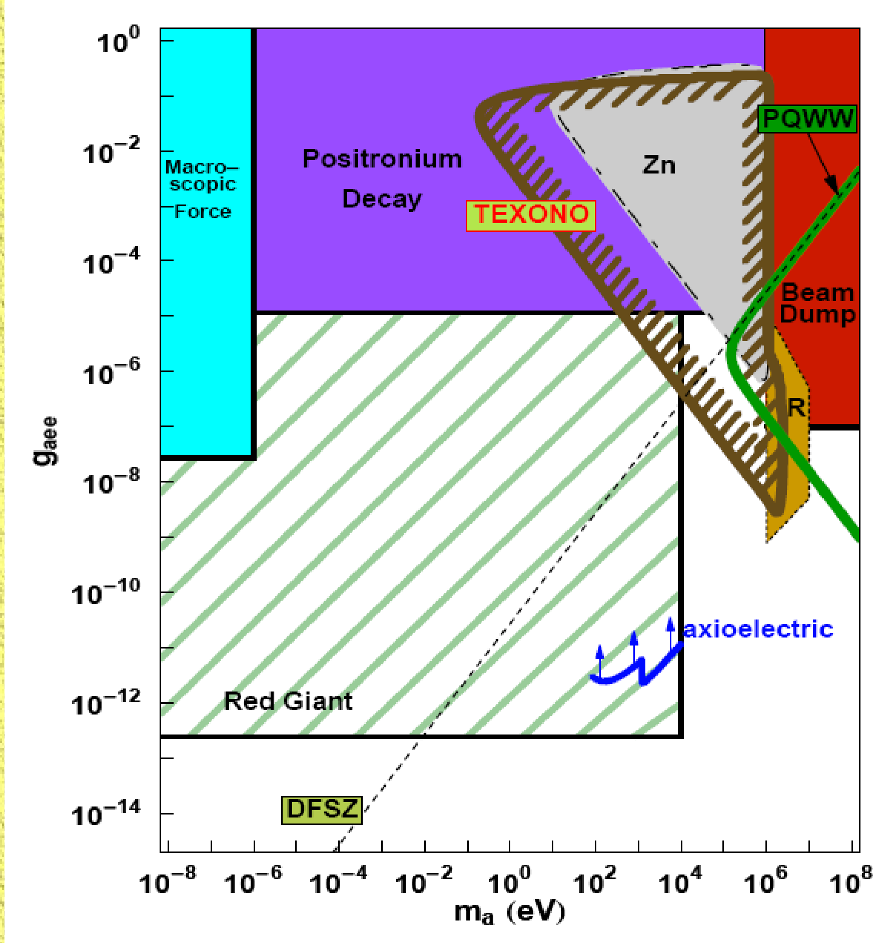


Exclusion Plot : Aγ Couplings at Low Mass



Exclusion Plot : general Aγ & Ae Couplings





TEXONO : 1 kg HPGe using possible Axions emissions from Reactor

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