暗物质探测
及超光速中微子

毕效军
中国科学院高能物理研究所

中国科技大学理论物理交叉中心，
2011/10/20

大 纲

- 暗物质存在证据
- 研究暗物质的意义
- 暗物质研究现状

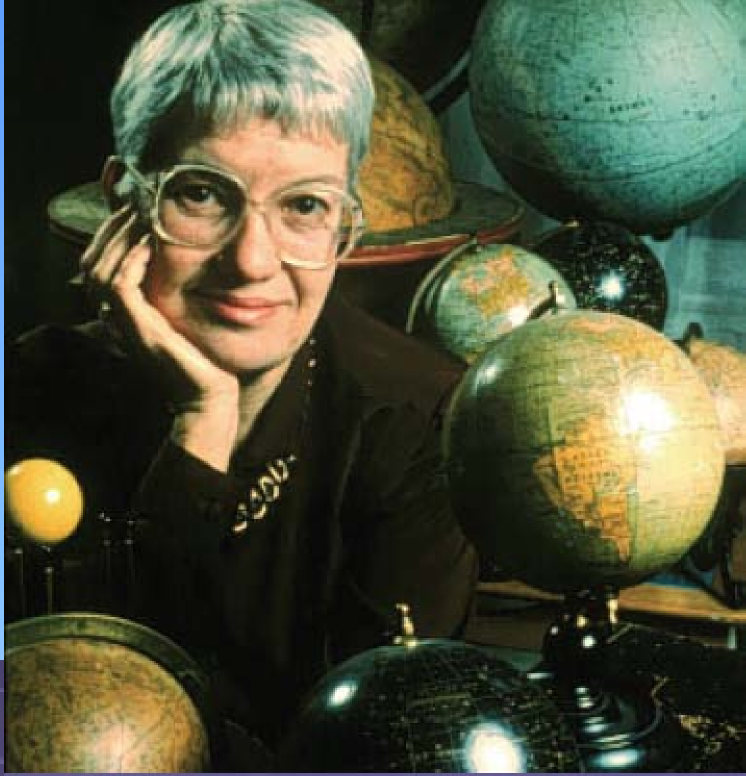
- 中微子超光速的研究

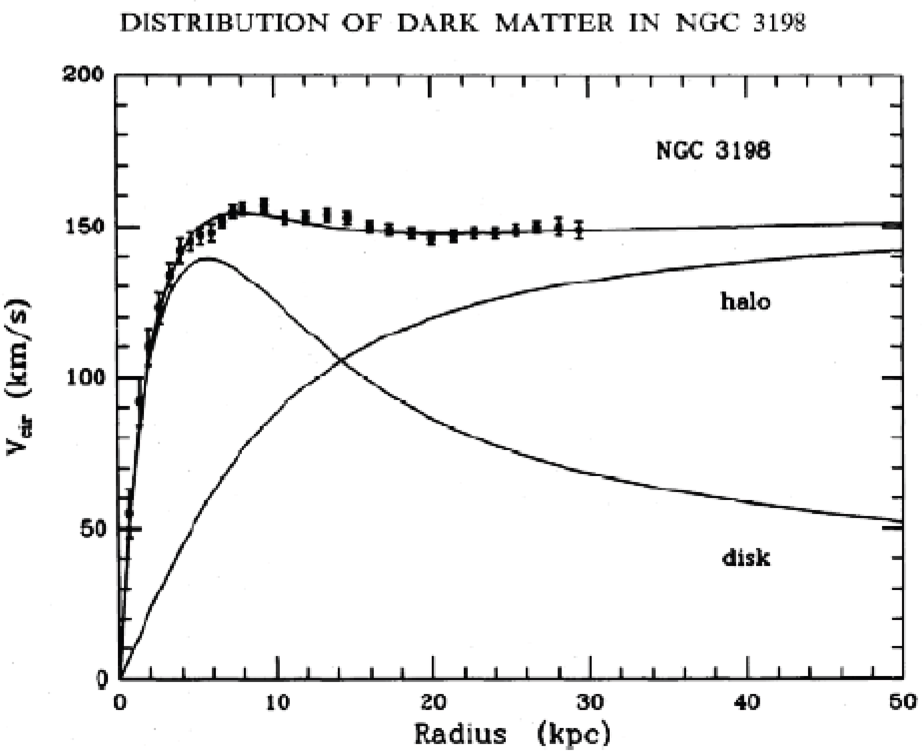
first glimpse of dark matter

- Fritz Zwicky: Used Doppler shift to measure peculiar velocities of galaxies at the edge of the Coma Cluster
  - Assuming virial equilibrium, found that most of the mass of the cluster must not be visible.

"If this [overdensity] is confirmed we would arrive at the astonishing conclusion that dark matter is present [in Coma] with a much greater density than luminous matter."
F. Zwicky, Helvetica Physica Acta 6: 110–127 (1933).

Vera Rubin





OBSERVED:
FLAT ROTATION
CURVE

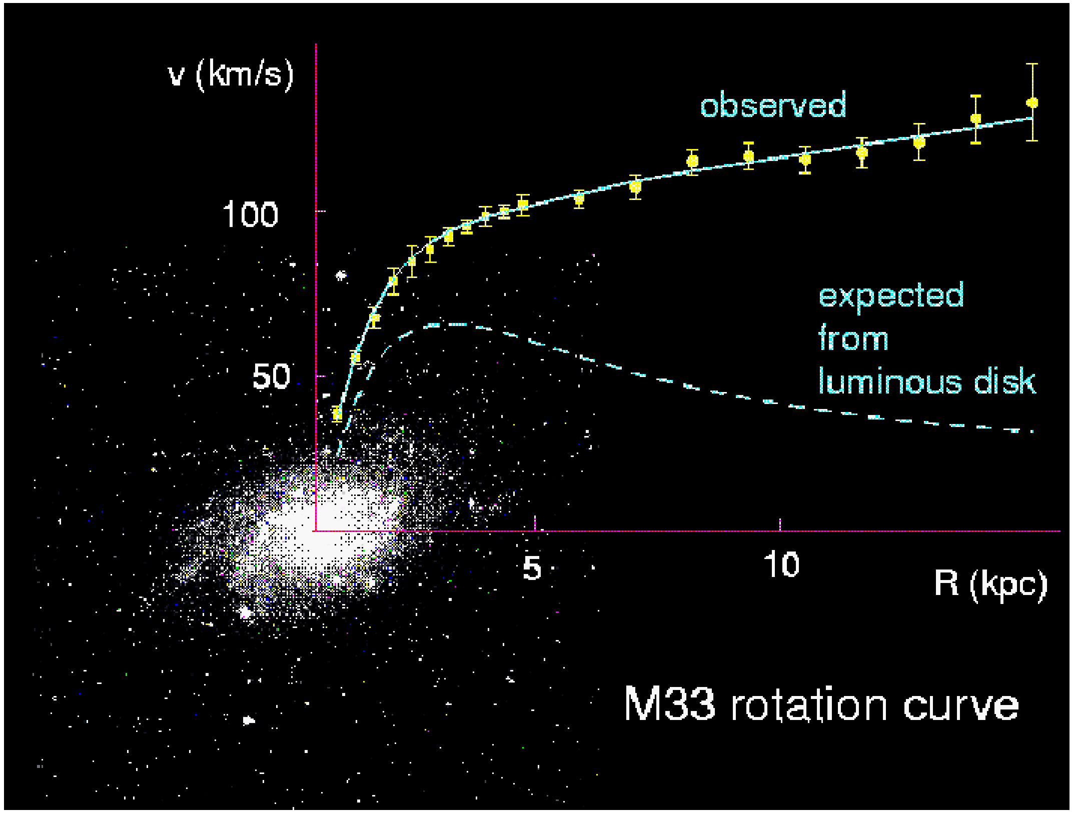
EXPECTED
FROM STARS

Evidences — galaxy scale (10kpc)

- From the Kepler's law, $v_{circ} = \sqrt{\frac{GM(r)}{r}}$ for r much larger than the luminous terms, you should have $v \propto r^{-1/2}$ However, it is flat or rises slightly.

- The most direct evidence of the existence of dark matter.

Corbelli & Salucci (2000); Bergstrom (2000)

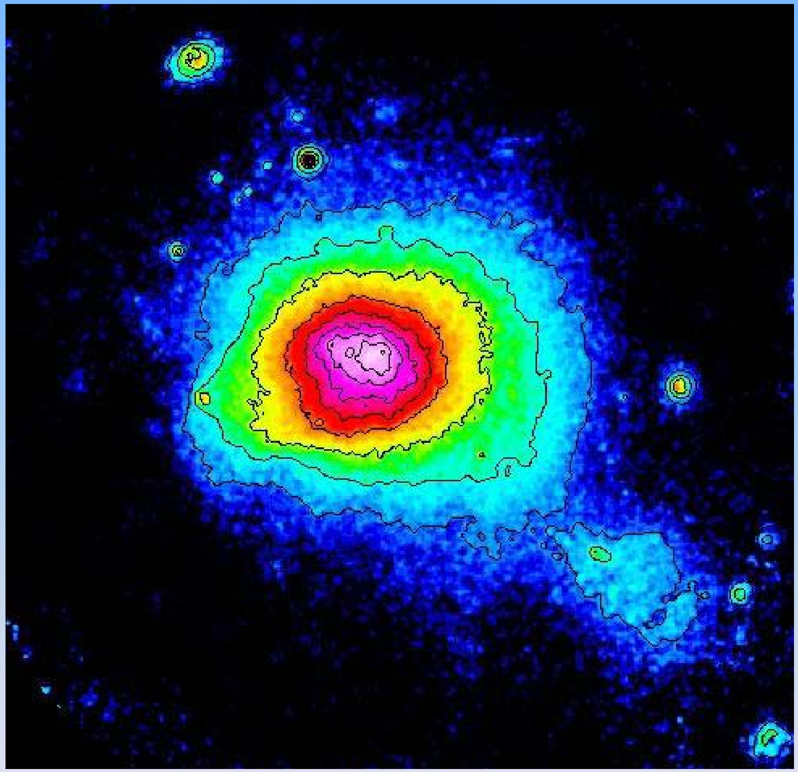


Evidences — cluster scale (Mpc)

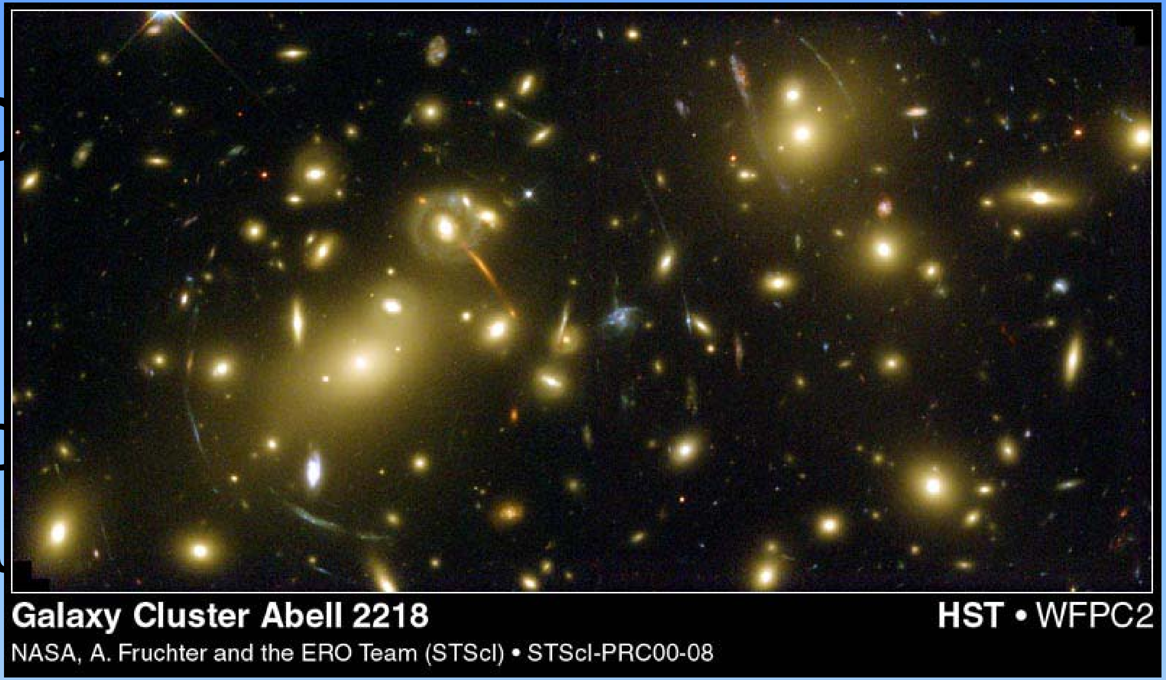
- Cluster contains hot gas which is at hydro static equilibrium. It's temperature follows,

$$\frac{GM(r)}{r^2} = -\frac{k_B T}{\mu m_H}\left[\frac{d\log\rho}{dr} + \frac{d\log T}{dr}\right]$$

- emission measures the temperature and $M/M_{visible}$=20

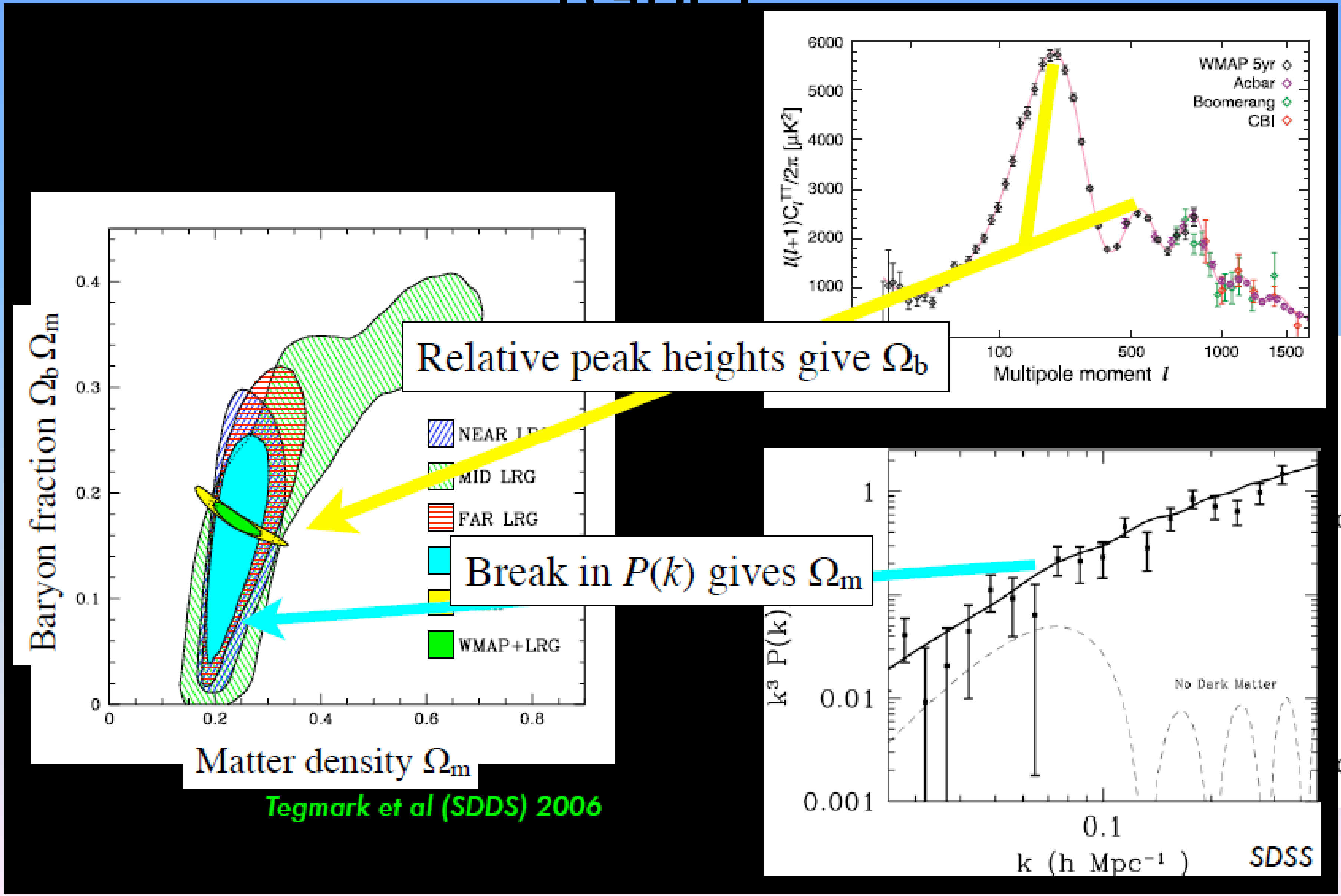


Evidenc

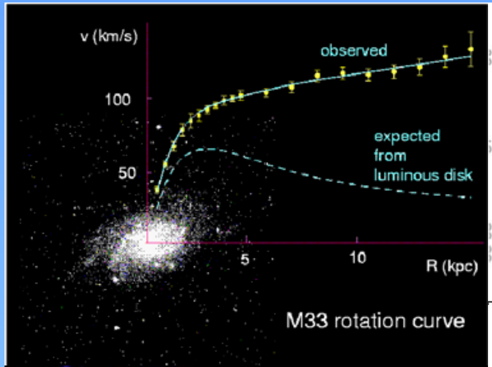


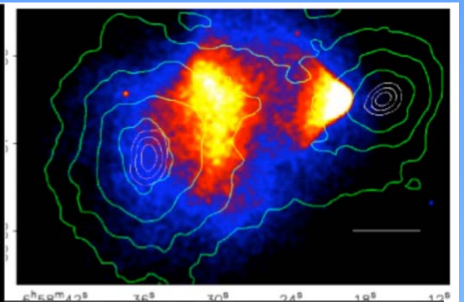
- Weak lensing
  images of bac
  foreground clu
  cluster mass.
- Sunyaev-Zeldovich distortion measures the distortion of CMB passing through cluster, which measure the temperature of the gas and therefore the mass of the cluster.
- …other measurements

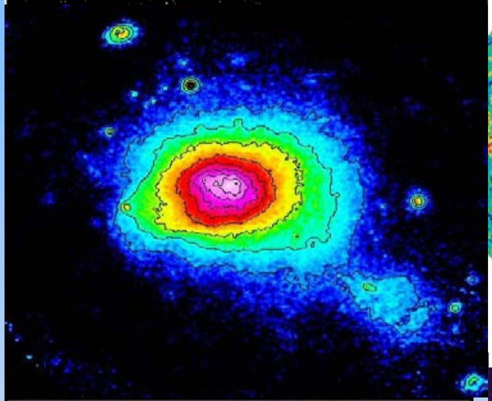
Evidences — cosmological scale (Gpc)

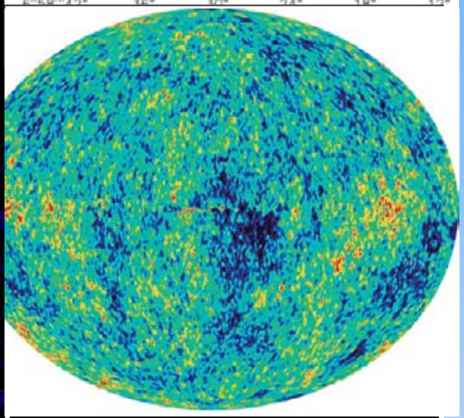


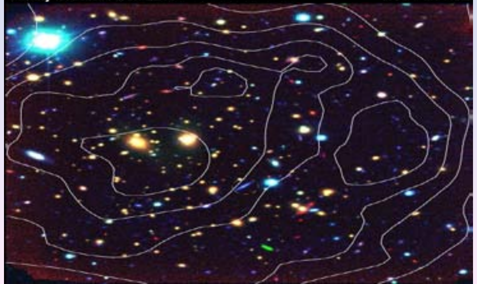
Standard cosmology

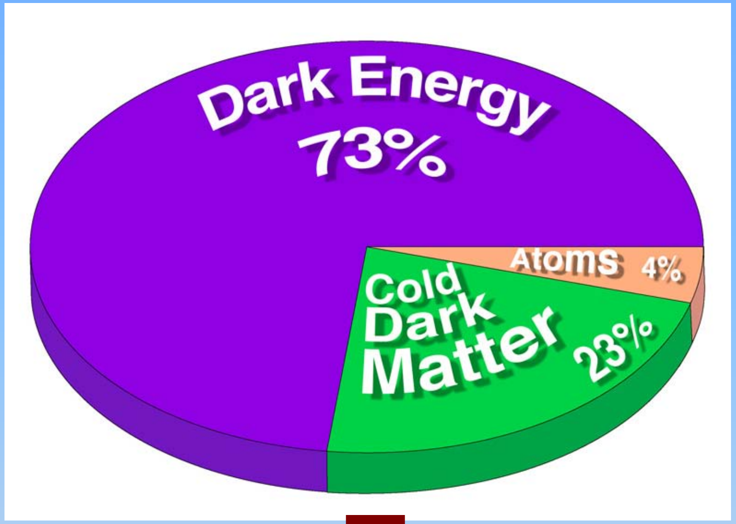








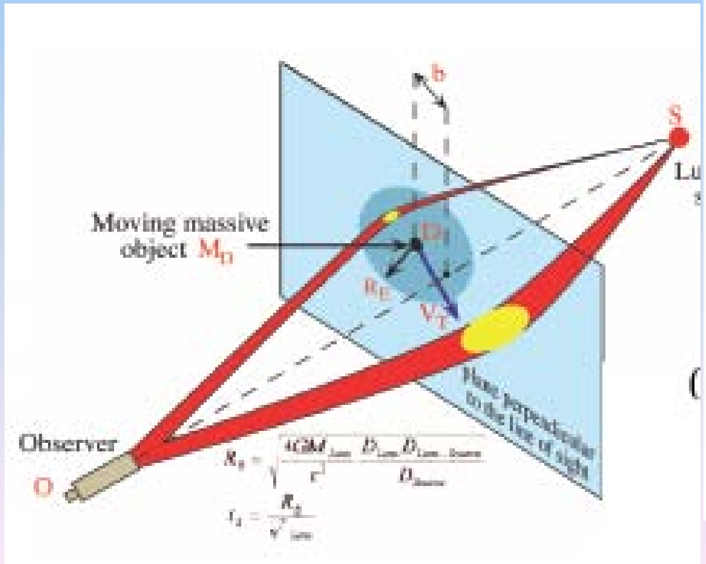


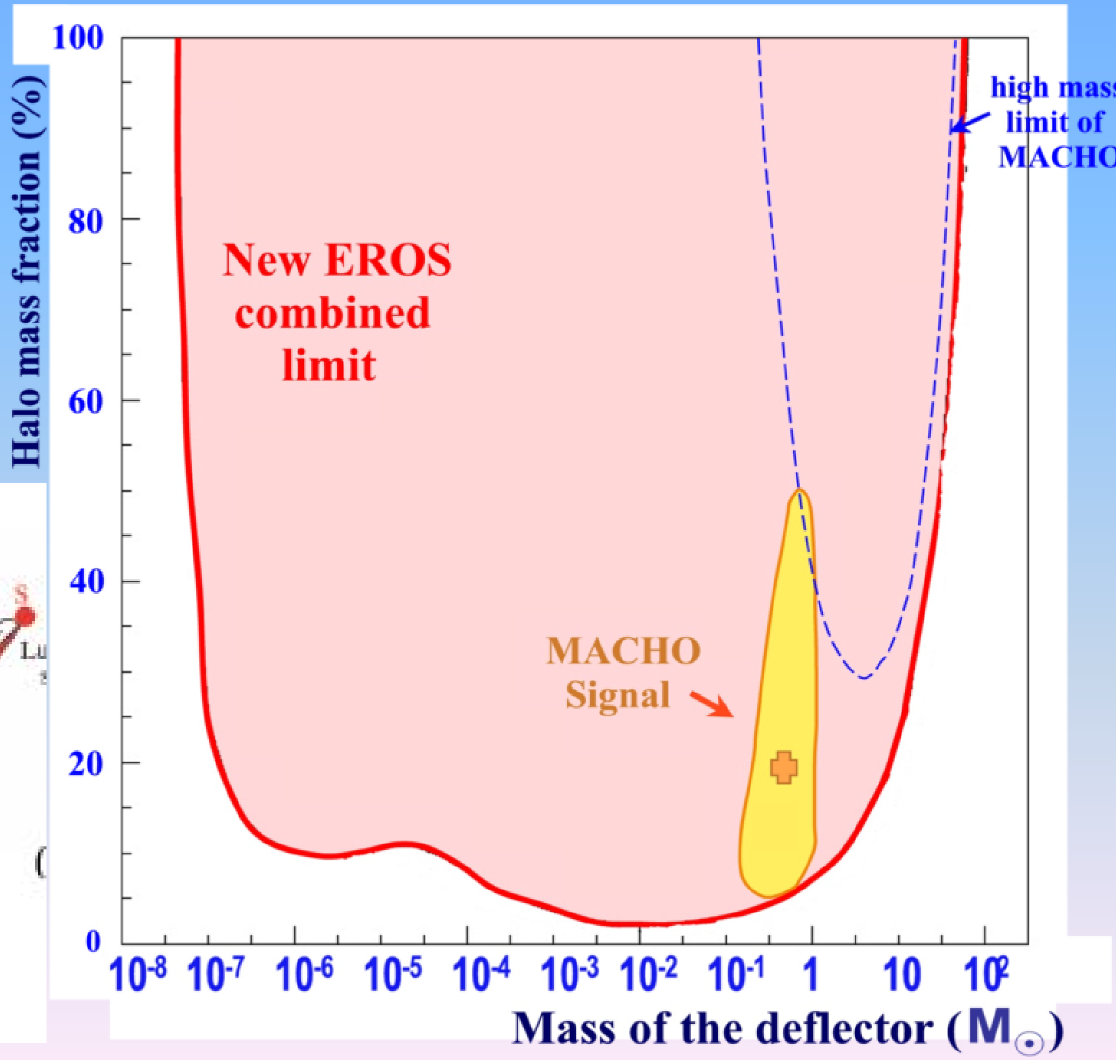


Dark matter (dark energy) exists in the universe. However, we have to figure out its property.

Nature of dark matter – non-baryonic cold dark matter

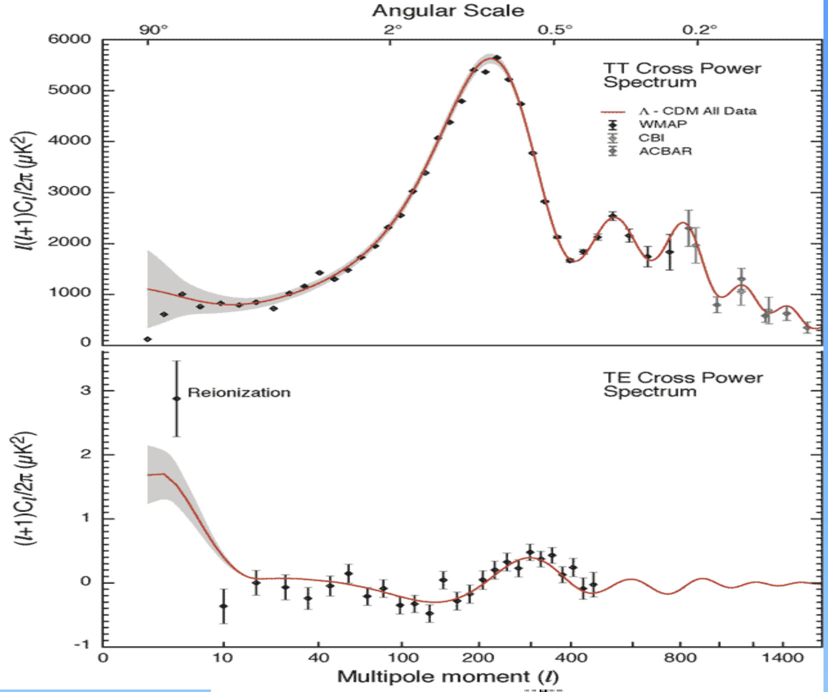
Not in compact form, such as black holes, neutron stars? (MACHO -MAssive Compact Halo Objects)

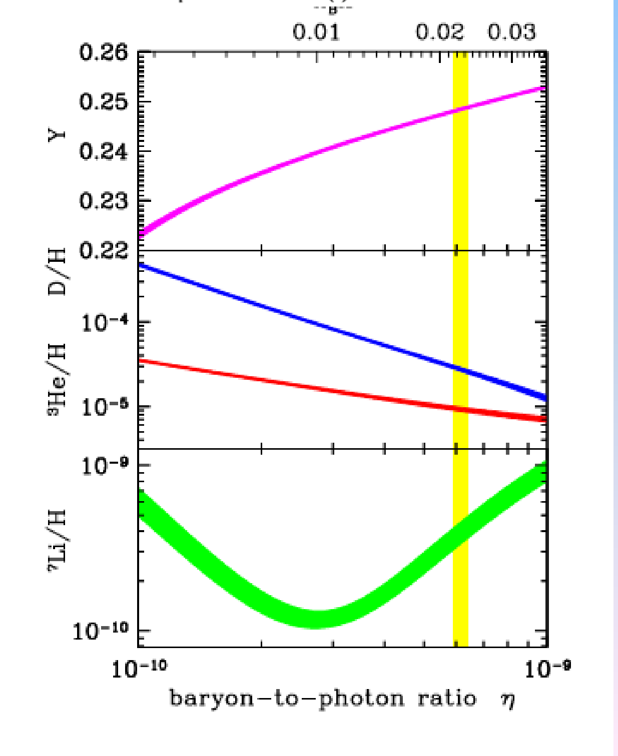




Non-baryonic

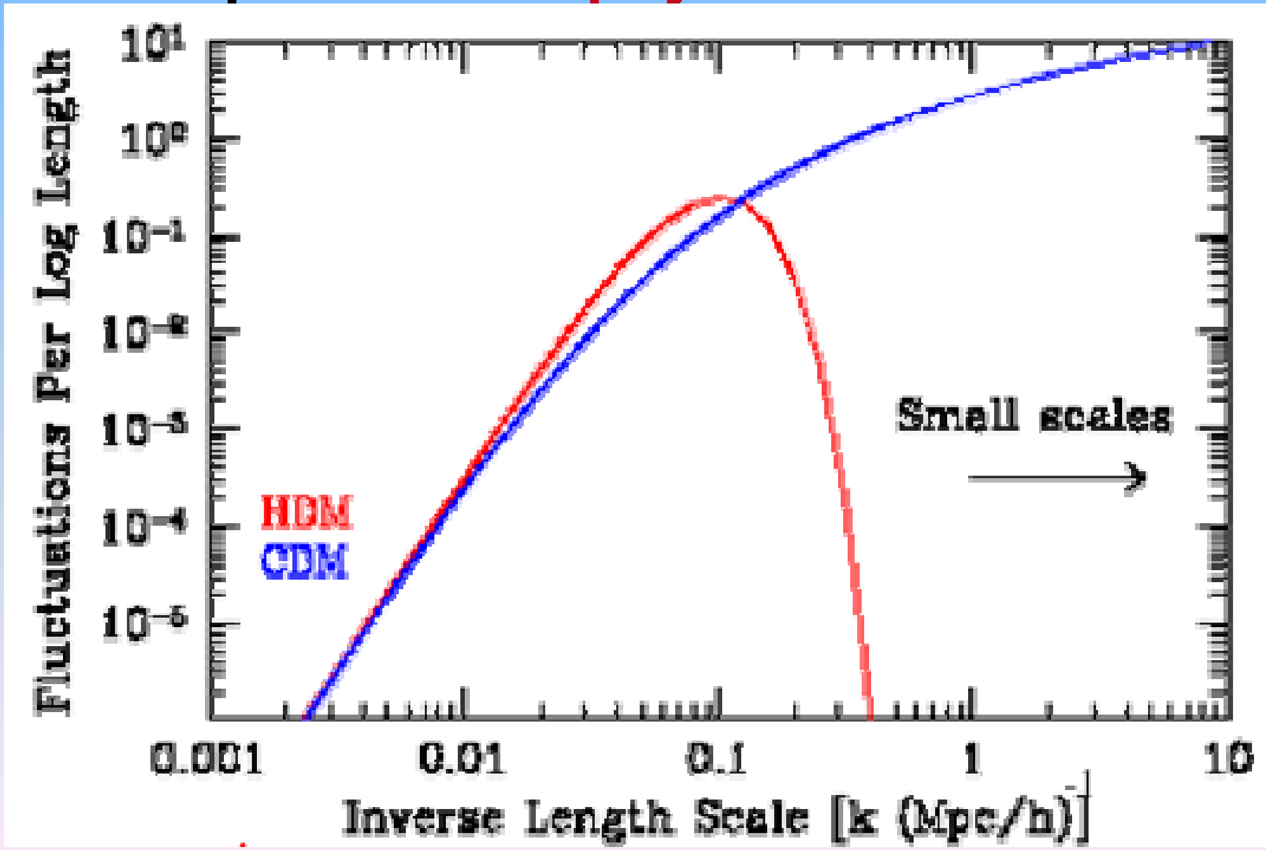
From BBN and CMB, it has $\Omega_B h^2$=0.02+-0.002. Therefore, most dark matter should be non-baryonic. $\Omega_{DM} h^2$=0.113+-0.009





New physics beyond the SM

Non-baryonic cold dark matter dominates the matter contents of the Universe. New particles beyond the standard model are required! New physics!



大 纲

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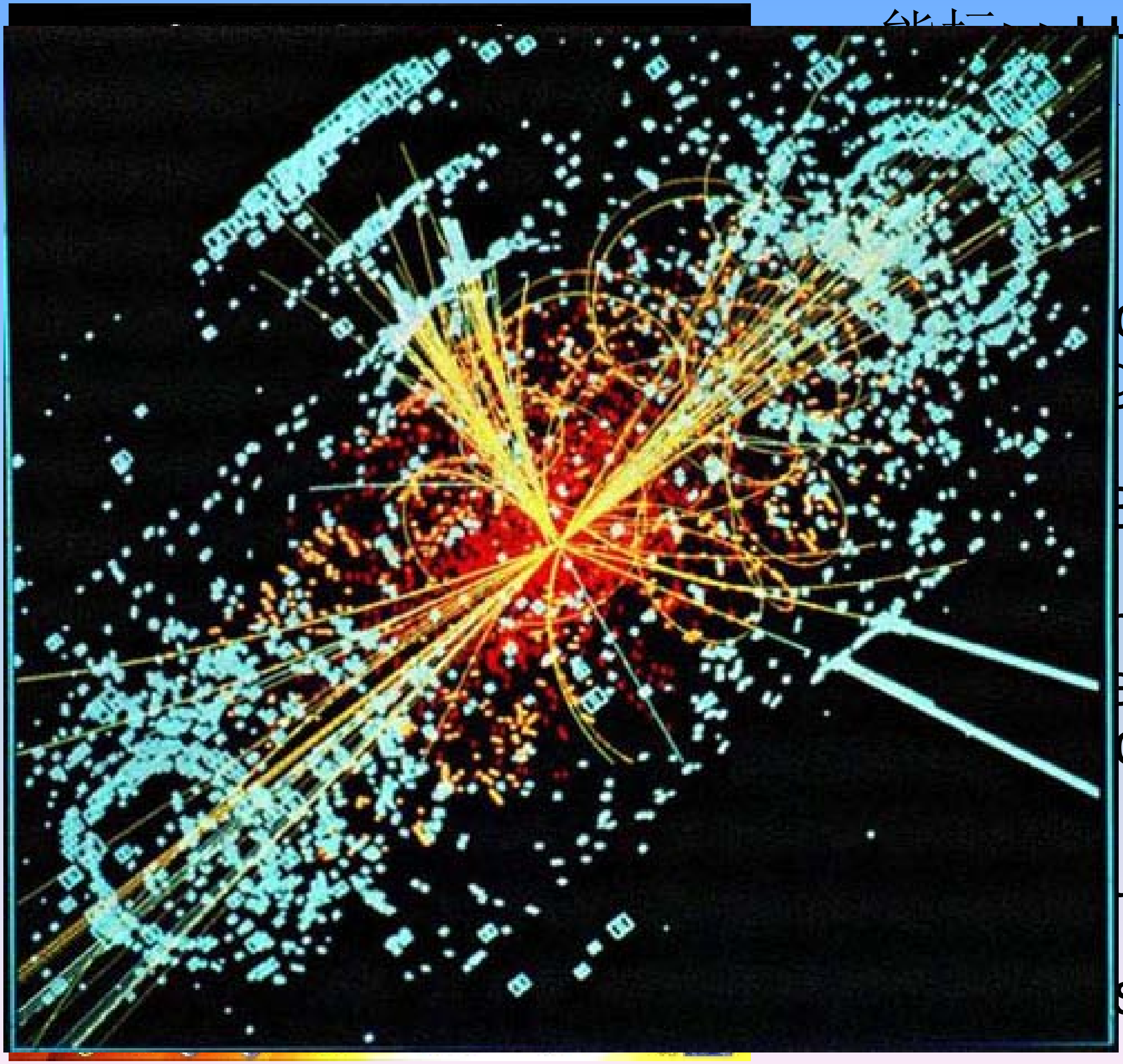
- 研究暗物质的意义
- 暗物质研究现状

The universe is the ultimate laboratory to study fundamental physics…….



HC能标

物理

record almost all
on of the reaction;
gy is limited.

has large enough
But we are very far
reaction at the Big
nly the relics (stable
energy) of the
can be observed

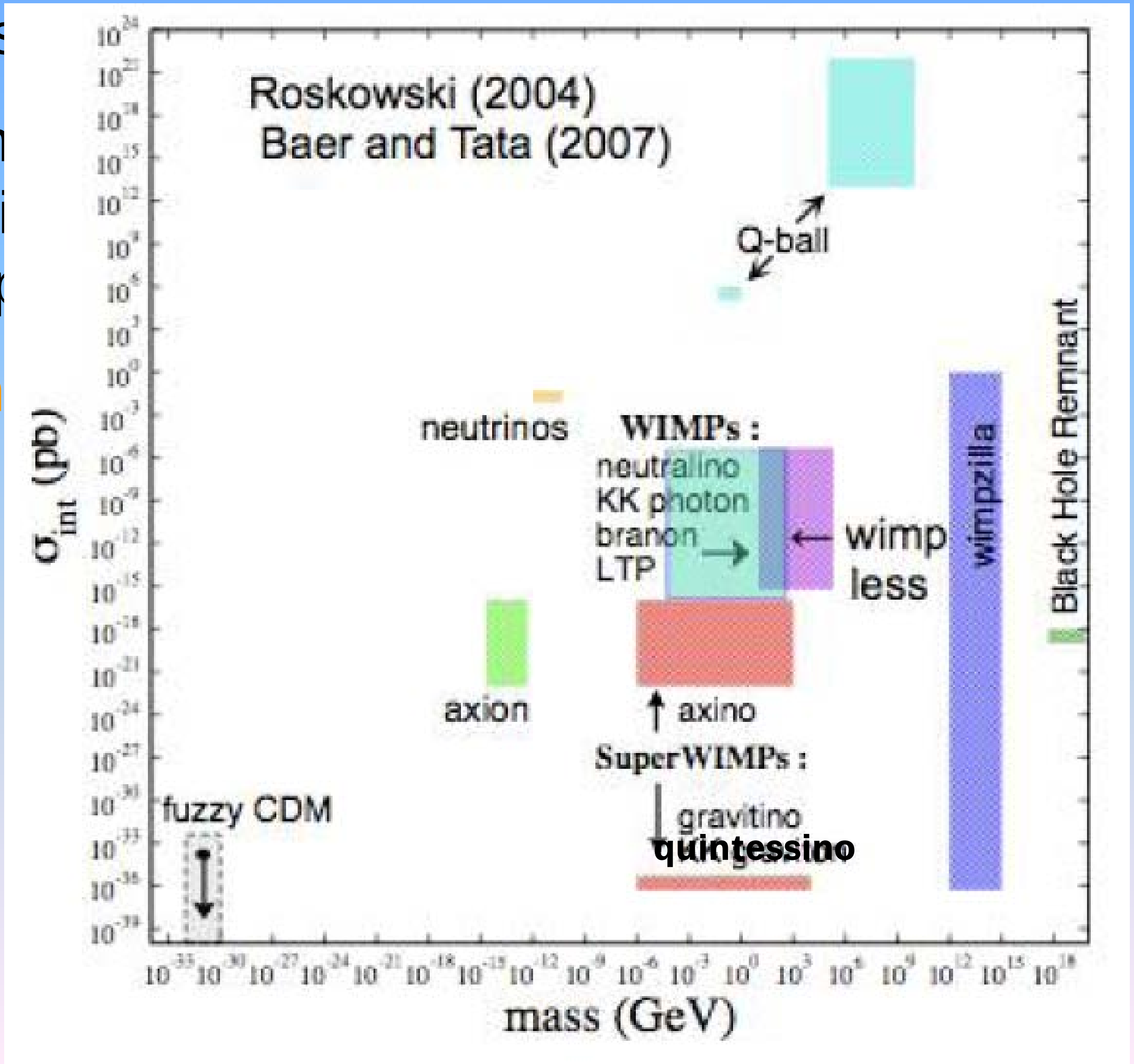
ucky if the relics of
Universe is just the
sing energy

标准模型—暗物质—宇宙演化

- 基于对撞机实验，建立了描述微观粒子作用的成功理论，基本粒子的标准模型（一般认为只是低能有效理论）
- 暗物质是宇宙大爆炸的产物，是宇宙早期能量更高时产生的，超出了对撞机的能量，是在观测宇宙演化中发现的（是新物理所预期的）
- 了解暗物质的性质帮助我们理解更深入的物质微观结构
- 暗物质是沟通宇宙演化和微观世界基本结构的桥梁，是目前粒子物理和宇宙学研究的焦点问题。

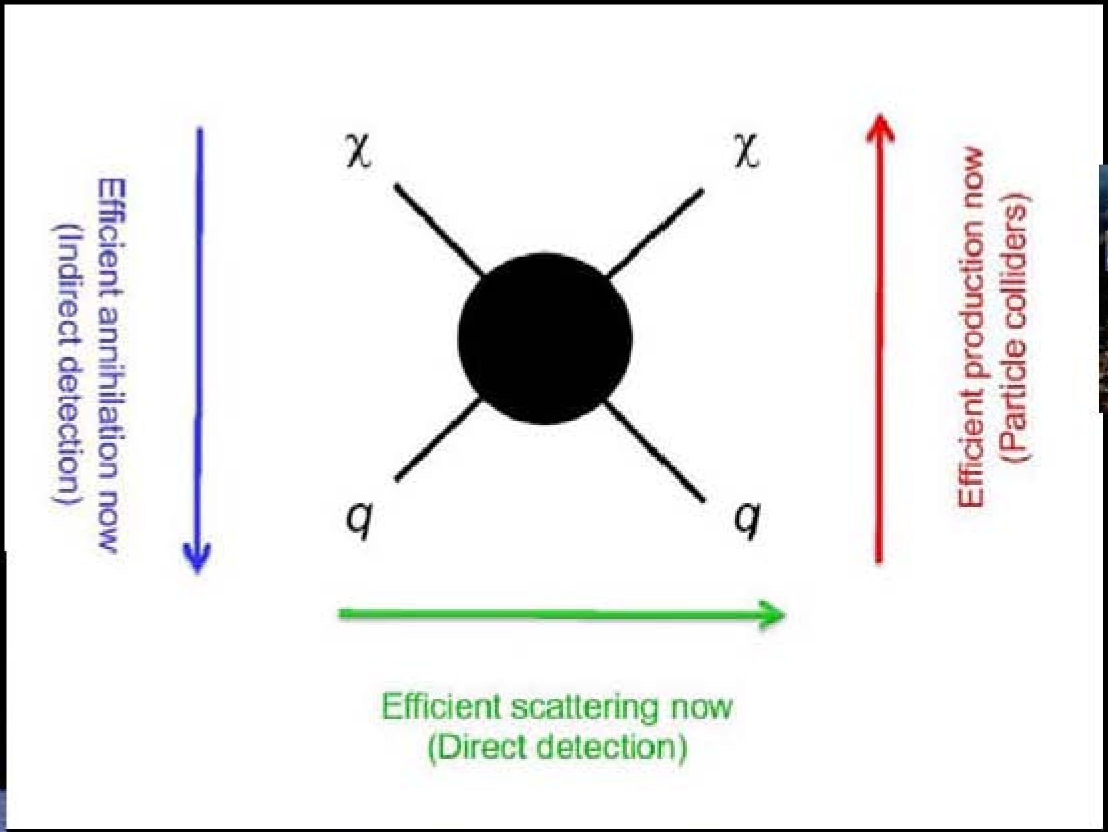
Candidates of the cold dark matter— stable、neutral、weak interacting

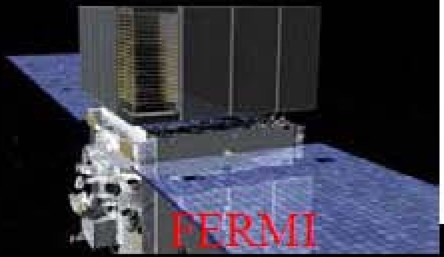
- There are dozens
- Weakly Interactin relics of Big Bang i independently prop
- such as neutralin



The WIMP miracle: for typical gauge couplings and masses of order the electroweak scale, $\Omega_{wimp}h^2 \approx 0.1$ (within factor of 10 or so)

Different approaches to search for Dark Matter





Adapted from P. Lipari

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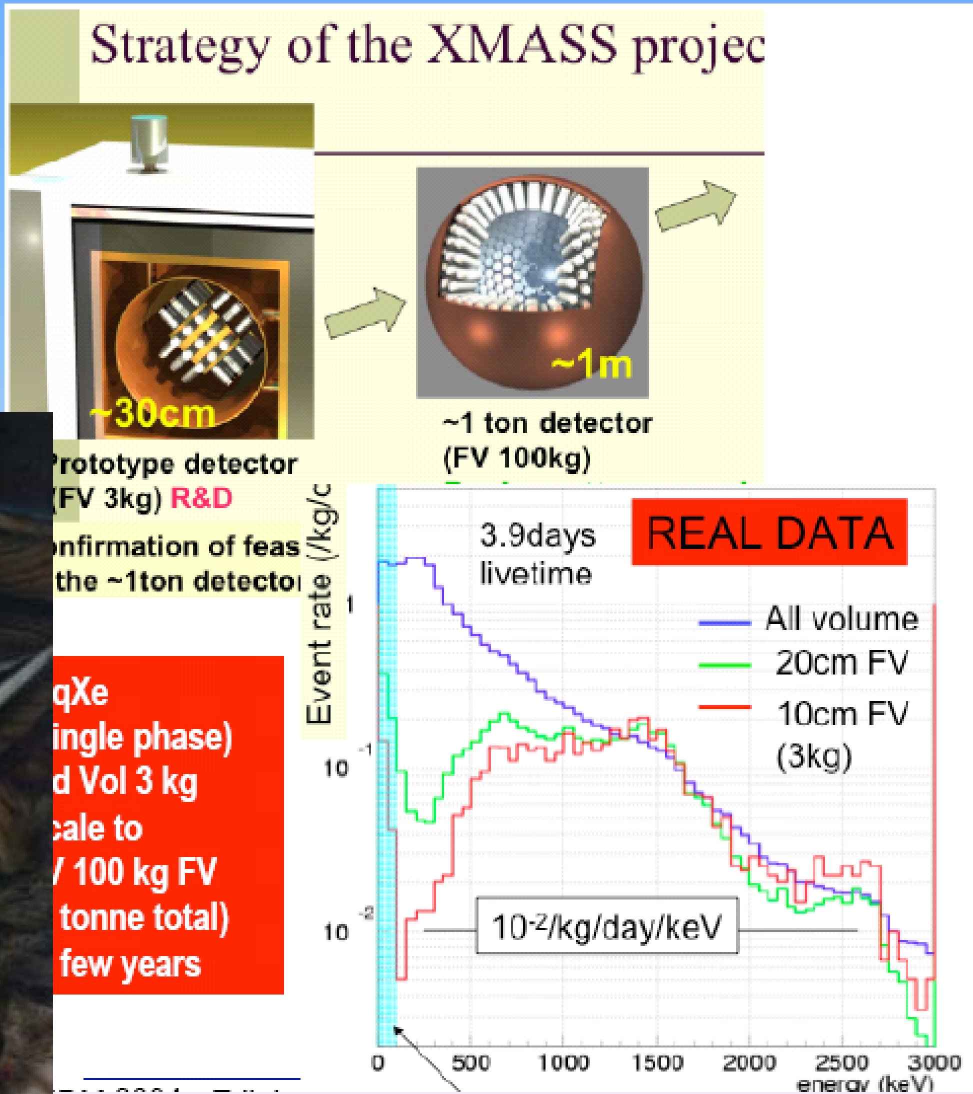
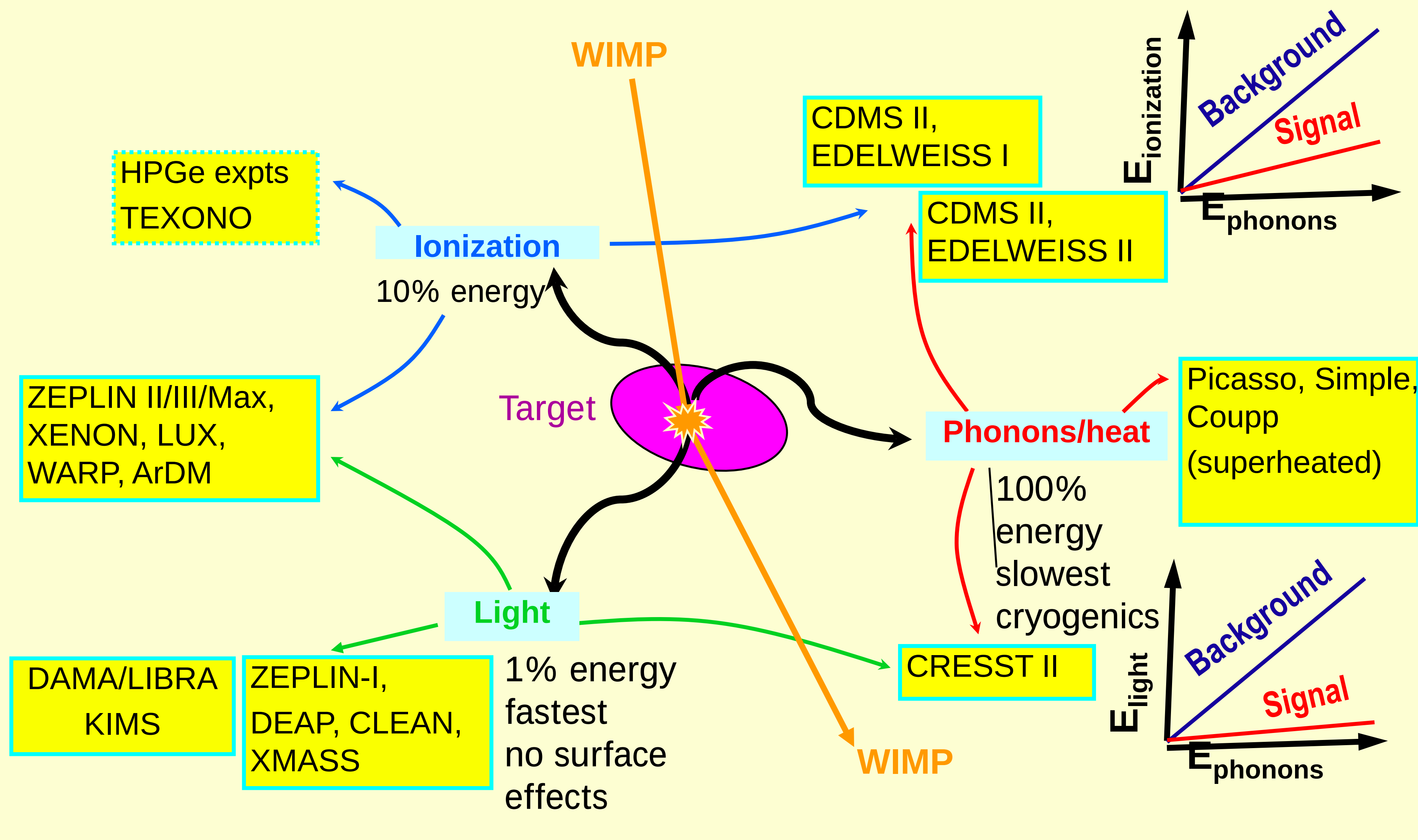
直接探测

(暗物质像空气一样充满整个银河系)

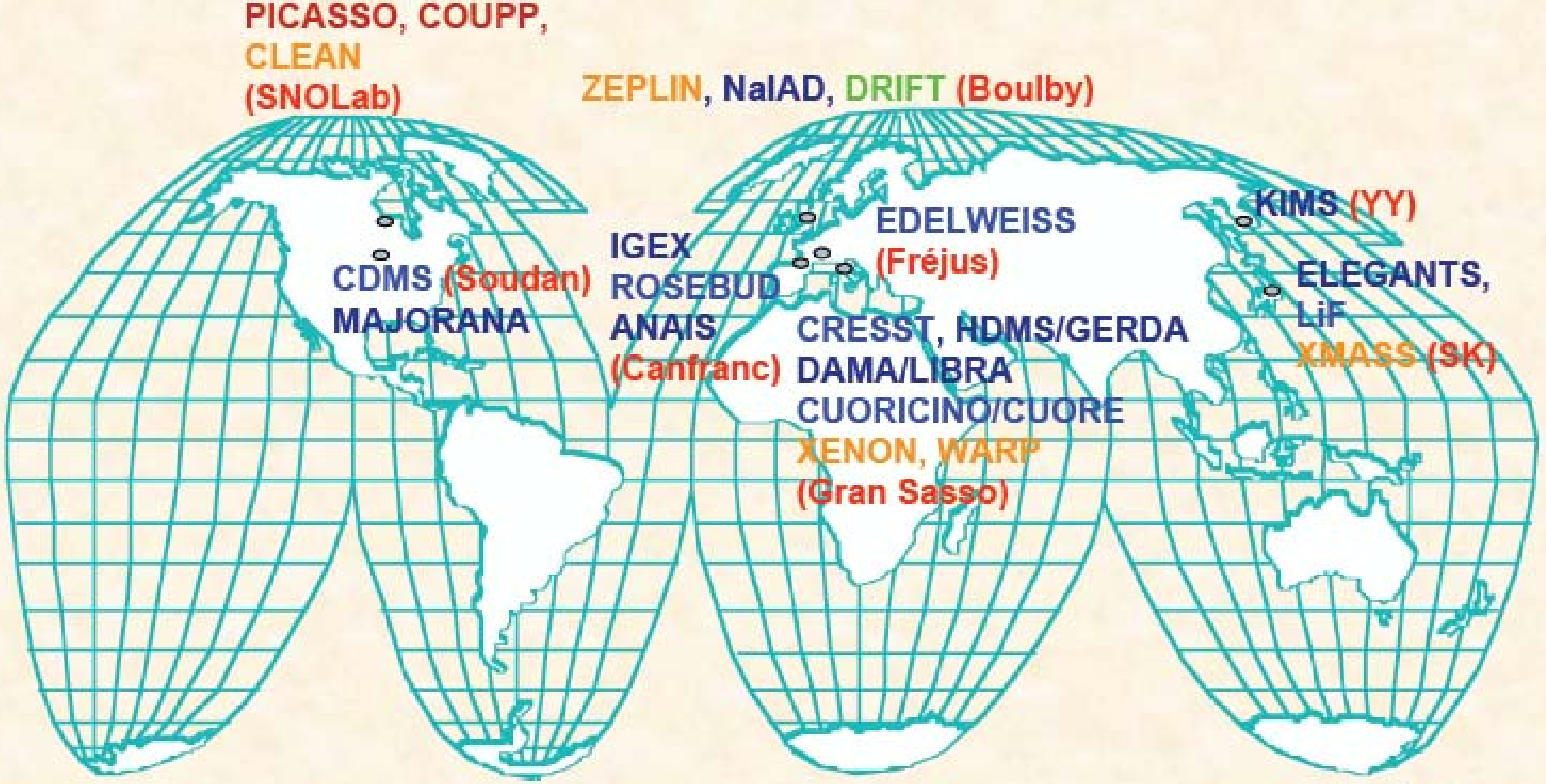
探测暗物质粒子与探测器碰撞所产生的信号



Detector Techniques - Present Focus : Nuclear Vs Electron recoils



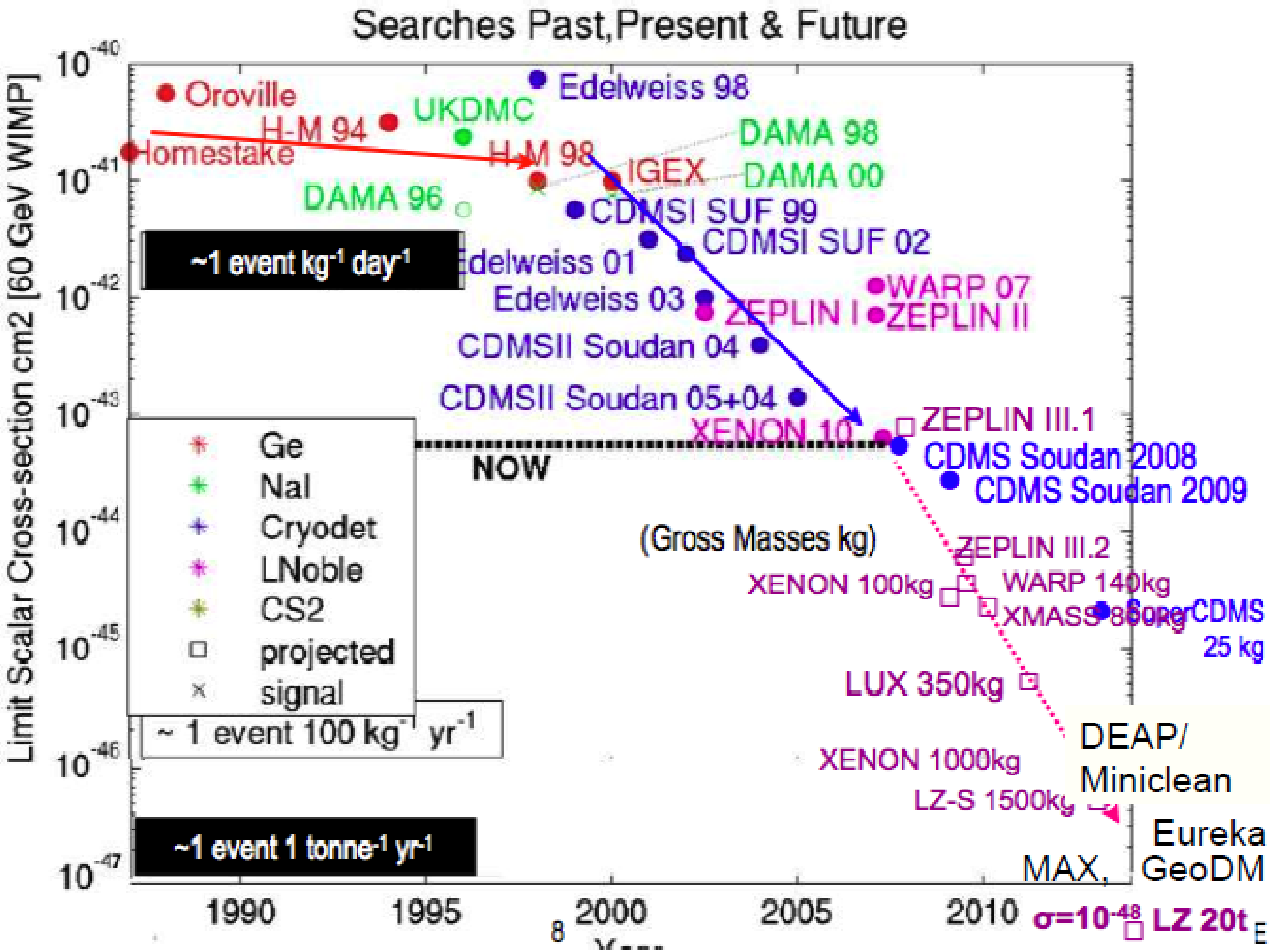
Wimp direct detection experiments



Liq scint
Cryo
Ge / solid scint
Gaz

ArDM, EURECA, SuperCDMS, XMASS II = 100kg to 1T projects

DM Direct Search Progress Over Time



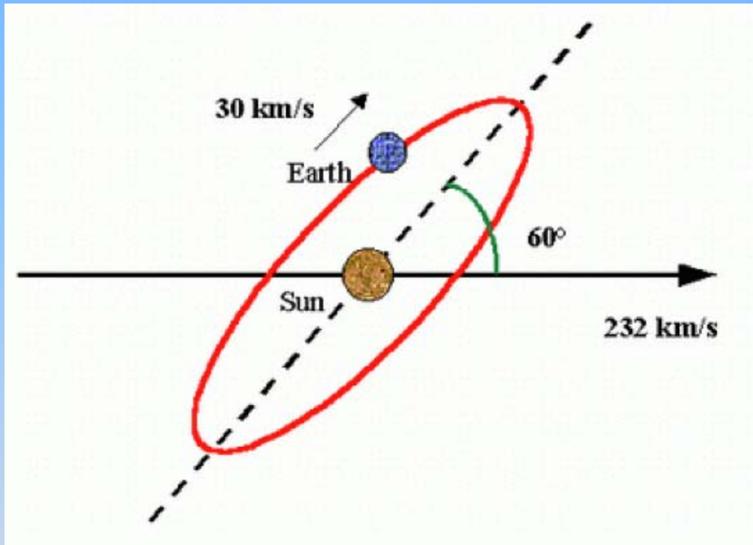
8

DAMA confirms the solar modulation signals at 9 **σ**

Velocity of the Earth and detection rate of DAMA can be given as

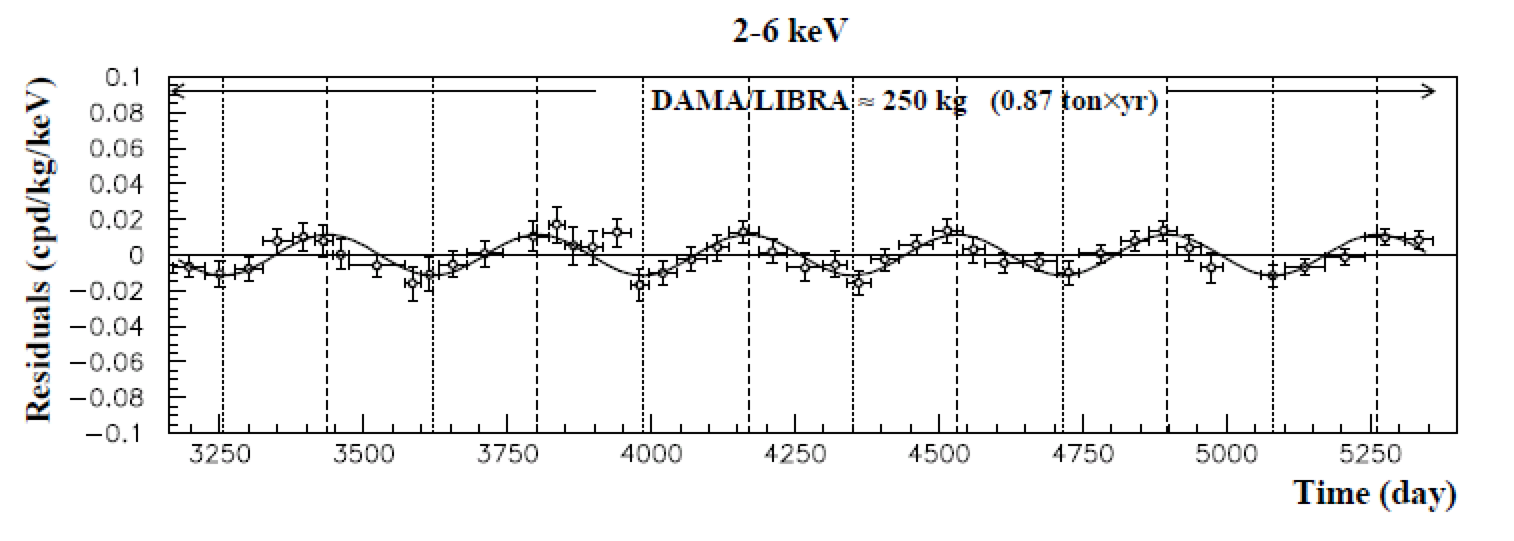
$$v_e = v_{\odot} + v_{orb} \cos\gamma \cos[\omega(t - t_0)]$$

$$R_i = R_i^0 + S_i^1 \cos[\omega(t - t_0)],$$



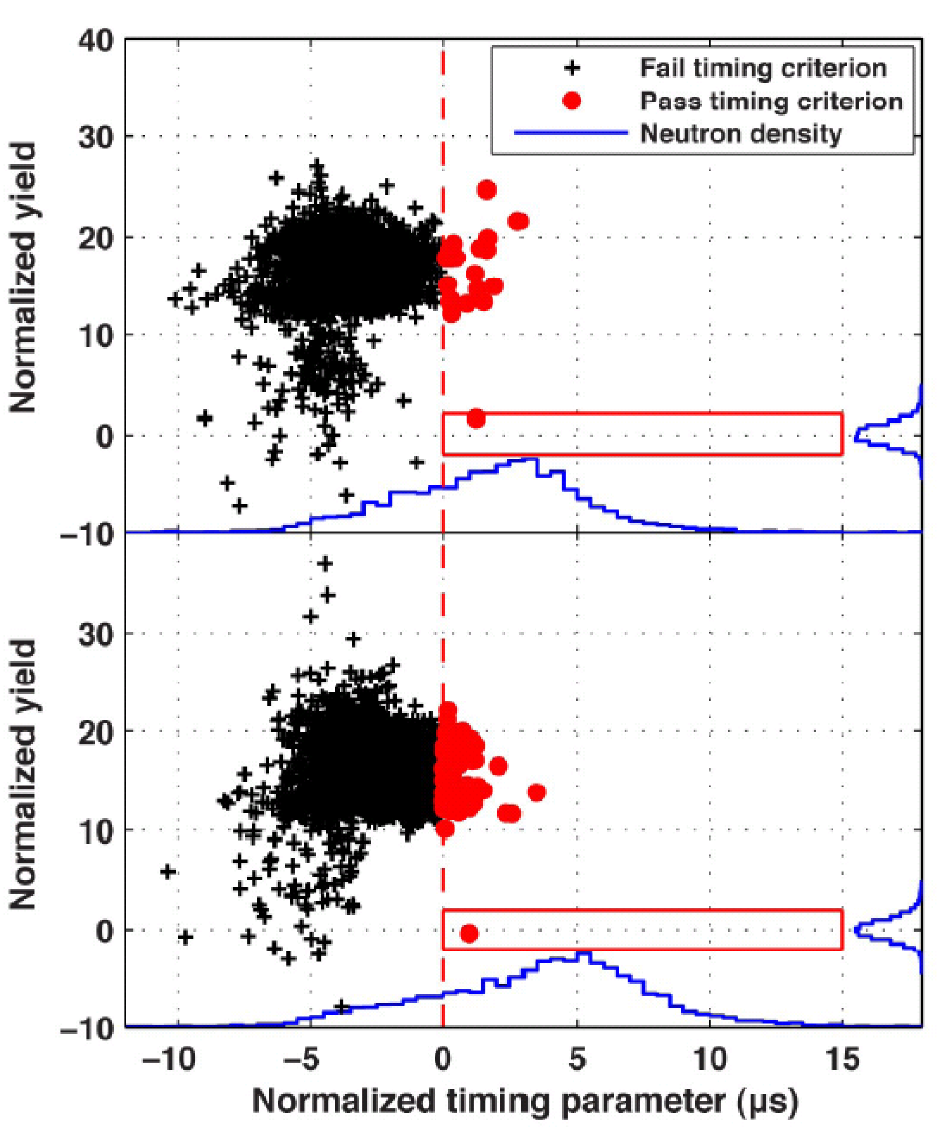
DAMA观测到9σ的年调制效应

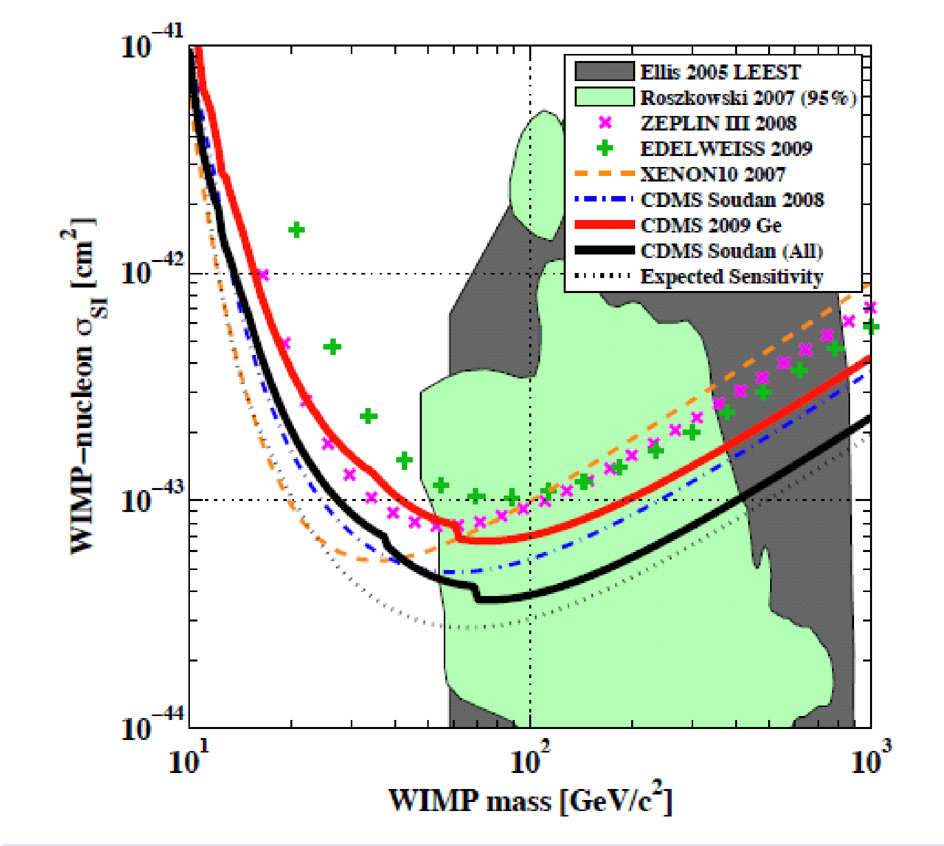
- Total exposure reaches 1.17 ton×yr,13yr

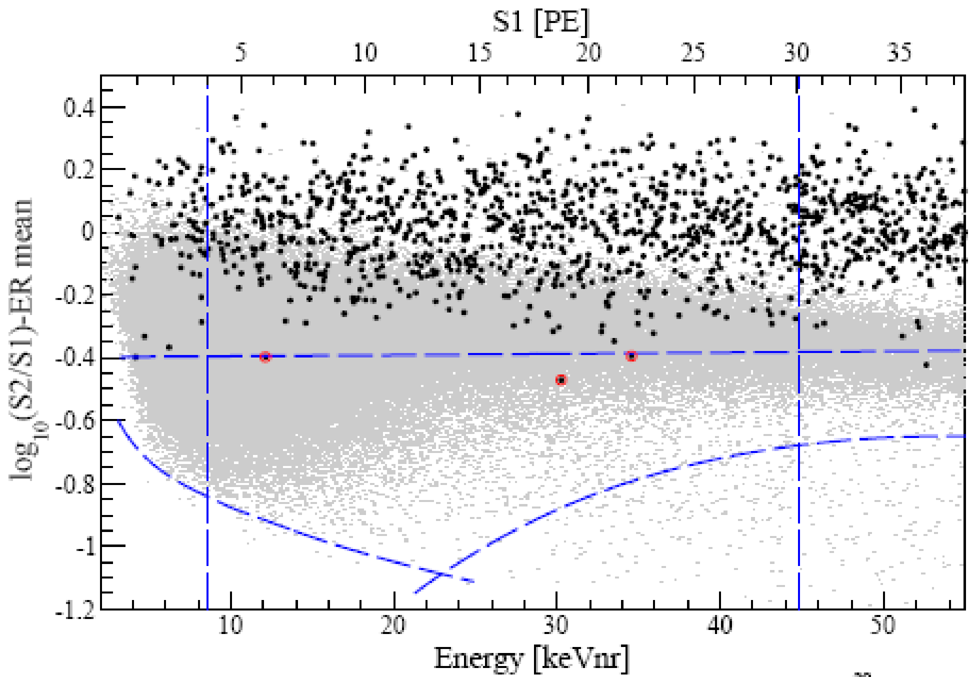


Energy interval	A (cpd/kg/keV)	$T = \frac{2\pi}{\omega}$ (yr)	t_0 (days)	C. L.
2-4	(0.0194±0.0022)	(0.996±0.002)	136±7	8.8σ
2-5	(0.0149±0.0016)	(0.997±0.002)	142±7	9.3σ
2-6	(0.0116±0.0013)	(0.999±0.002)	146±7	8.9σ

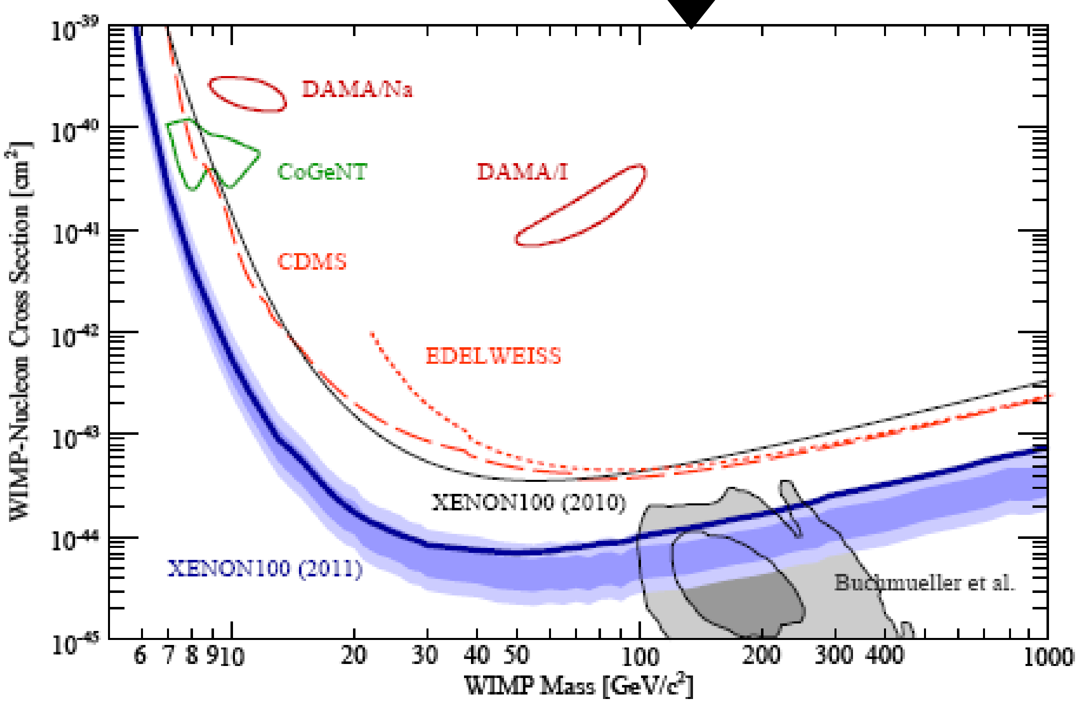
CDMSII的两个事例（2009 Dec）



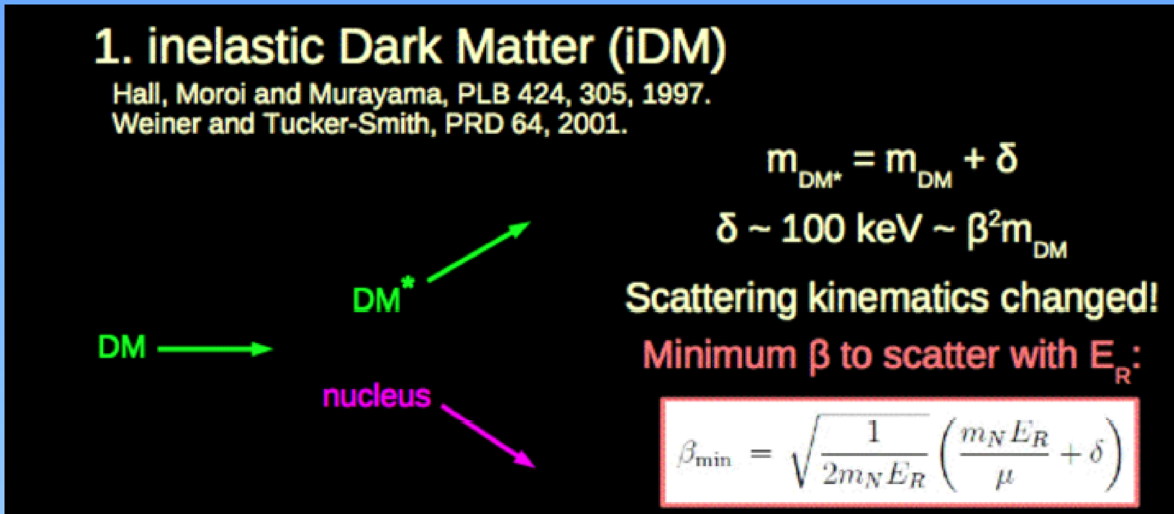


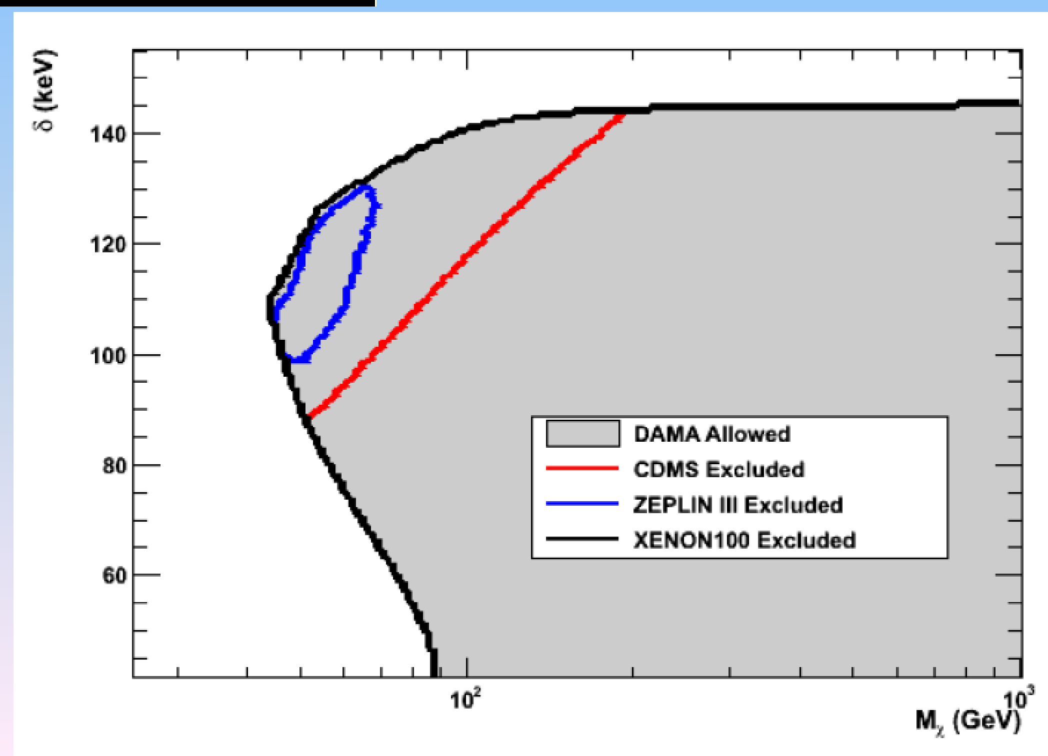


Isothermal, Maxwellian,
v_0=220km/s,v_{esp}=544km/s,
ρ_0=0.3GeV/cm^3



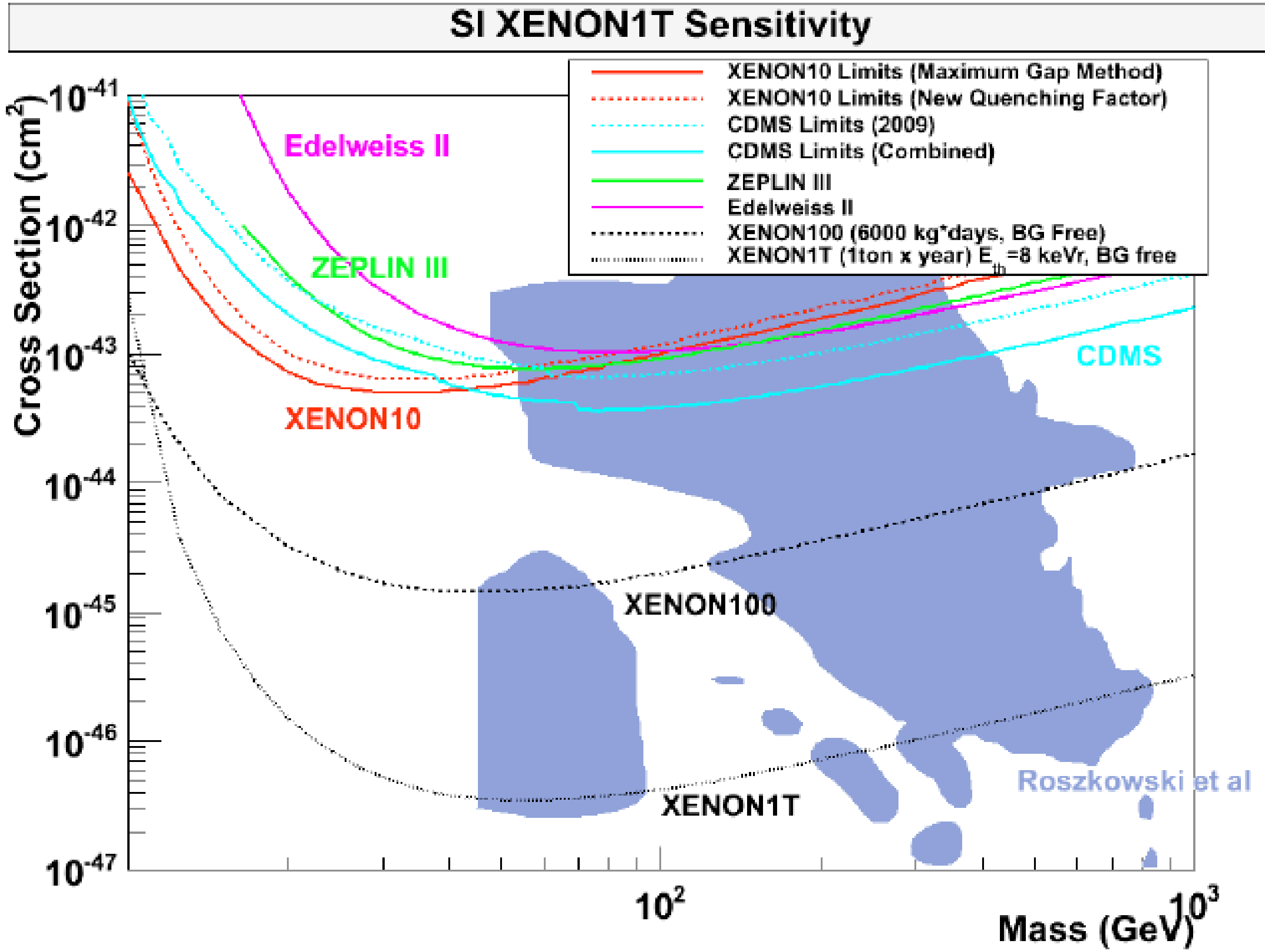
DAMA参数空间被XENON排除



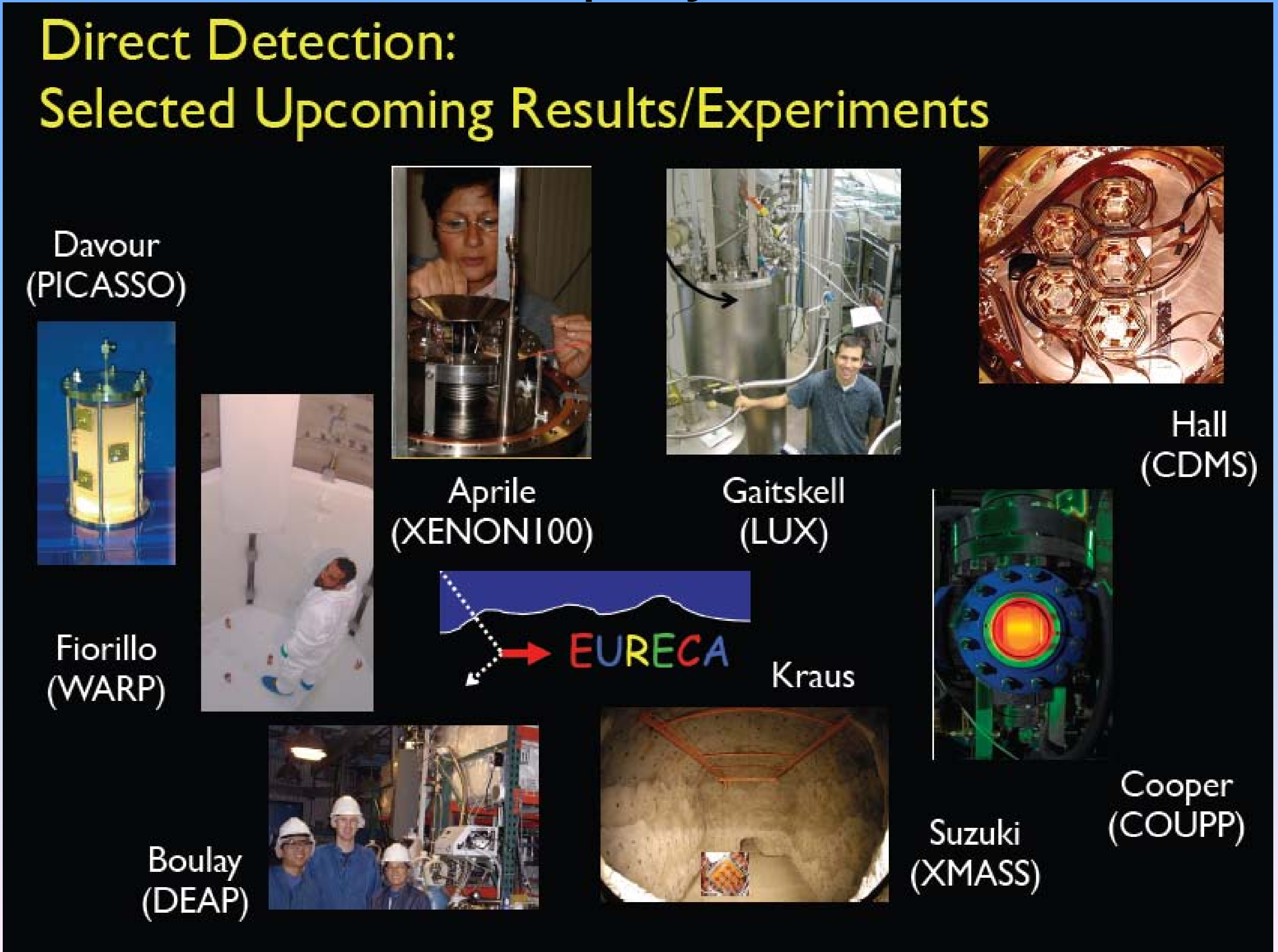


By Elena Aprile

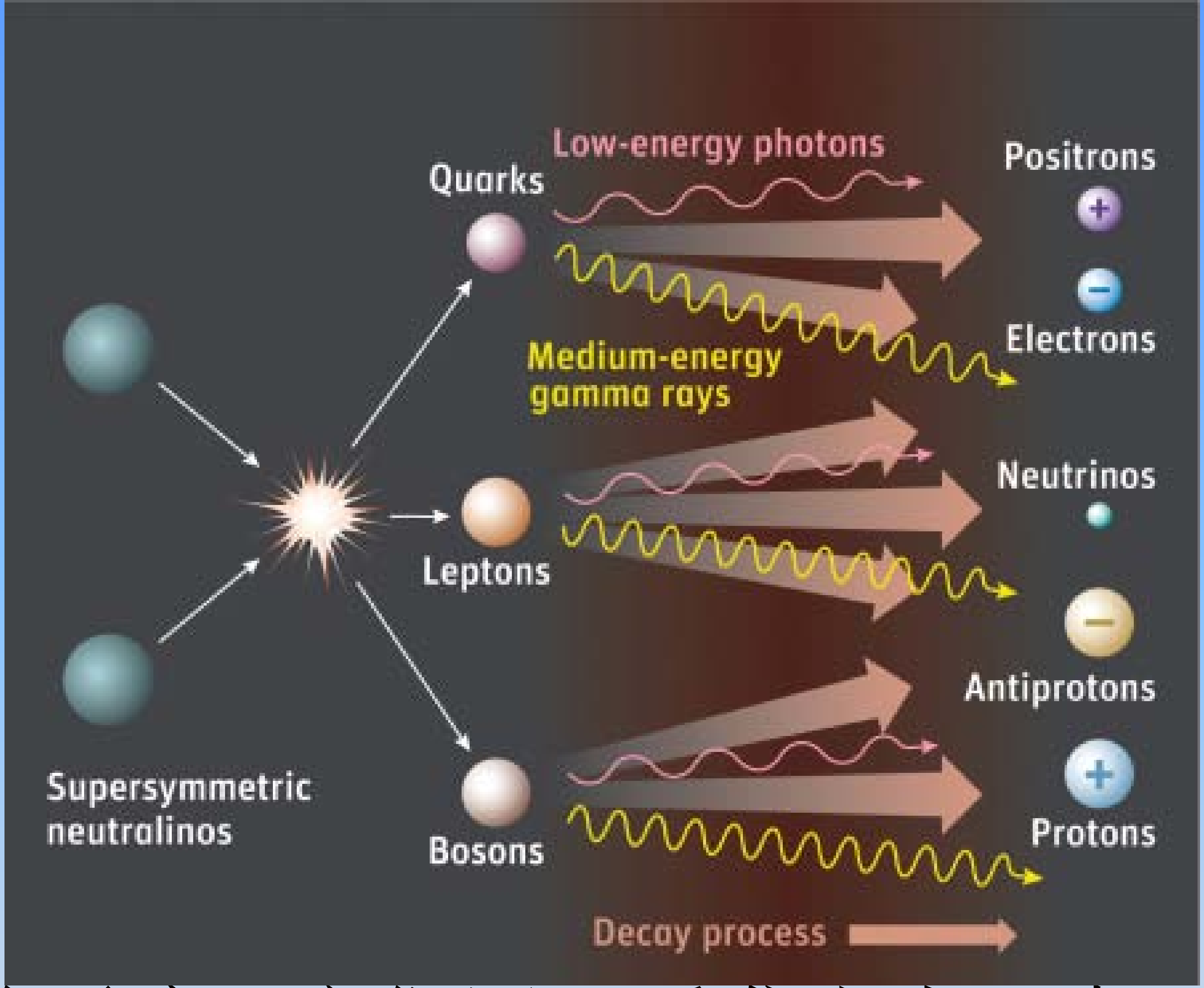
Spin-Independent Projected Sensitivity



New experiments and sensitivity improves rapidly



间接探测

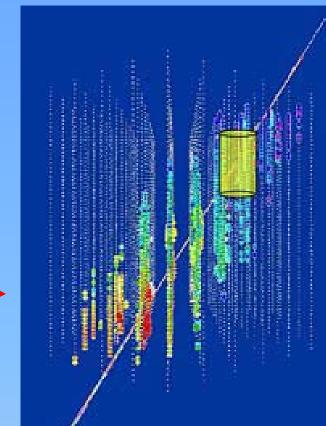


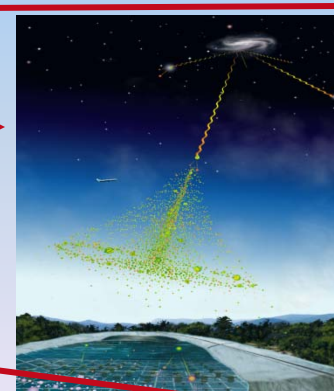
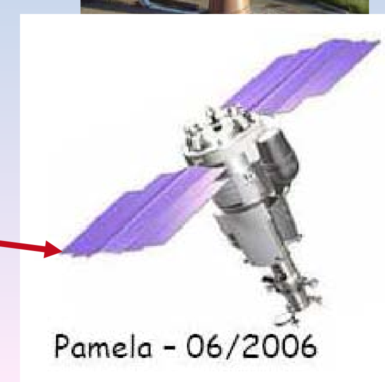
- 暗物质并不暗：它们湮灭后发出光，中微子，和带电粒子的宇宙线。

$$\chi^0\chi^0 \rightarrow l\bar{l}, q\bar{q}, 2W^{\pm}, 2Z^0, 2H^0, Z^0H^0, W^+H^-, gg$$

What Tools Do We Use?

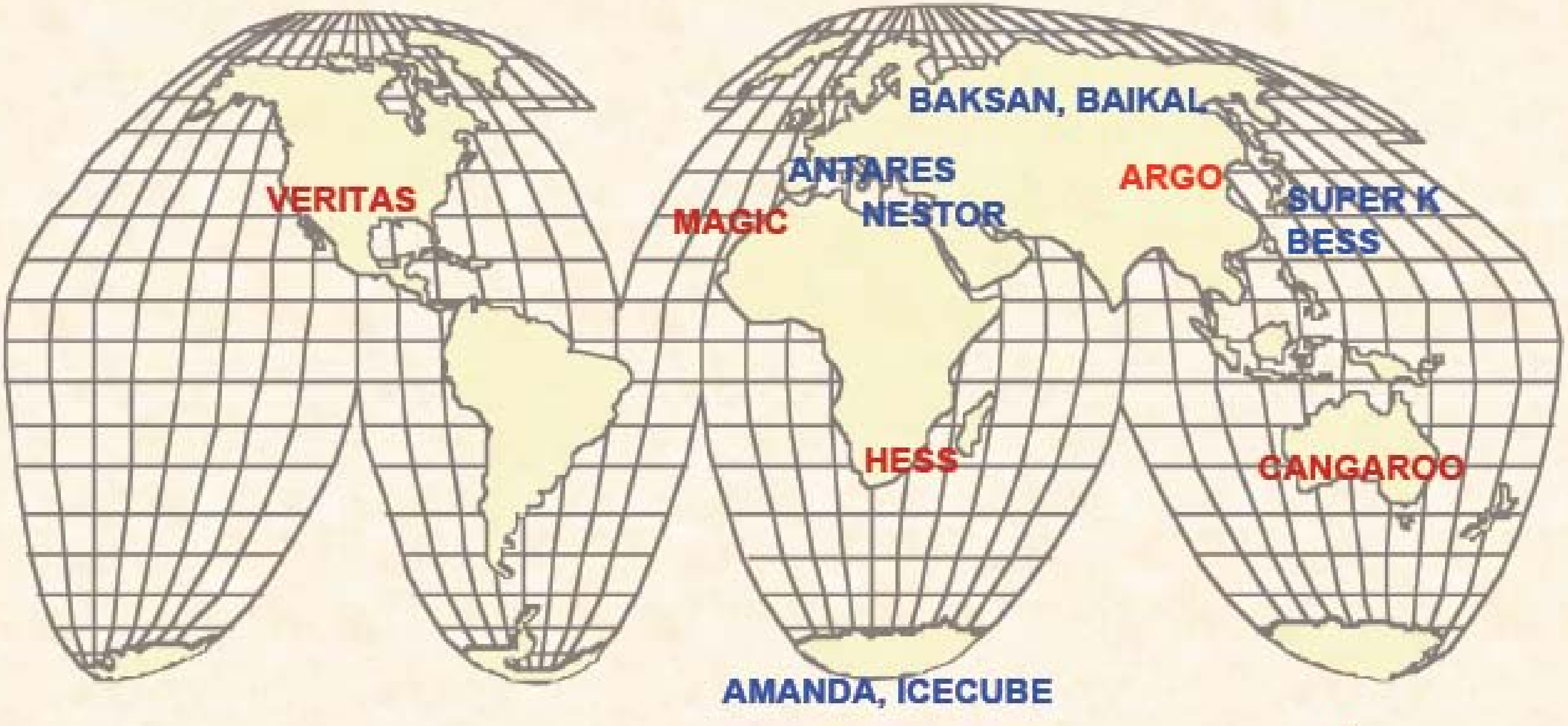
- **LHC**
- **Auger** and **HiRes** measure the highest energy cosmic ray flux, spectrum, and anisotropy
- **ICECube** searches for TeV neutrino sources – the most direct signature of hadronic accelerators
- **Fermi** detects thousands of new GeV sources
- **VERITAS, HESS, MAGIC**, and CANGAROO image and measure spectra and variability of TeV sources
- **Milagro/HAWC, Asγ/ARGO** image large-scale structures and searches for new and transient TeV sources
- **AMS02** (space-based antimatter search), **PAMELA** measure ANTIPROTON, POSITRON
- *PLANCK/SNAP*

Wimp indirect detection experiments

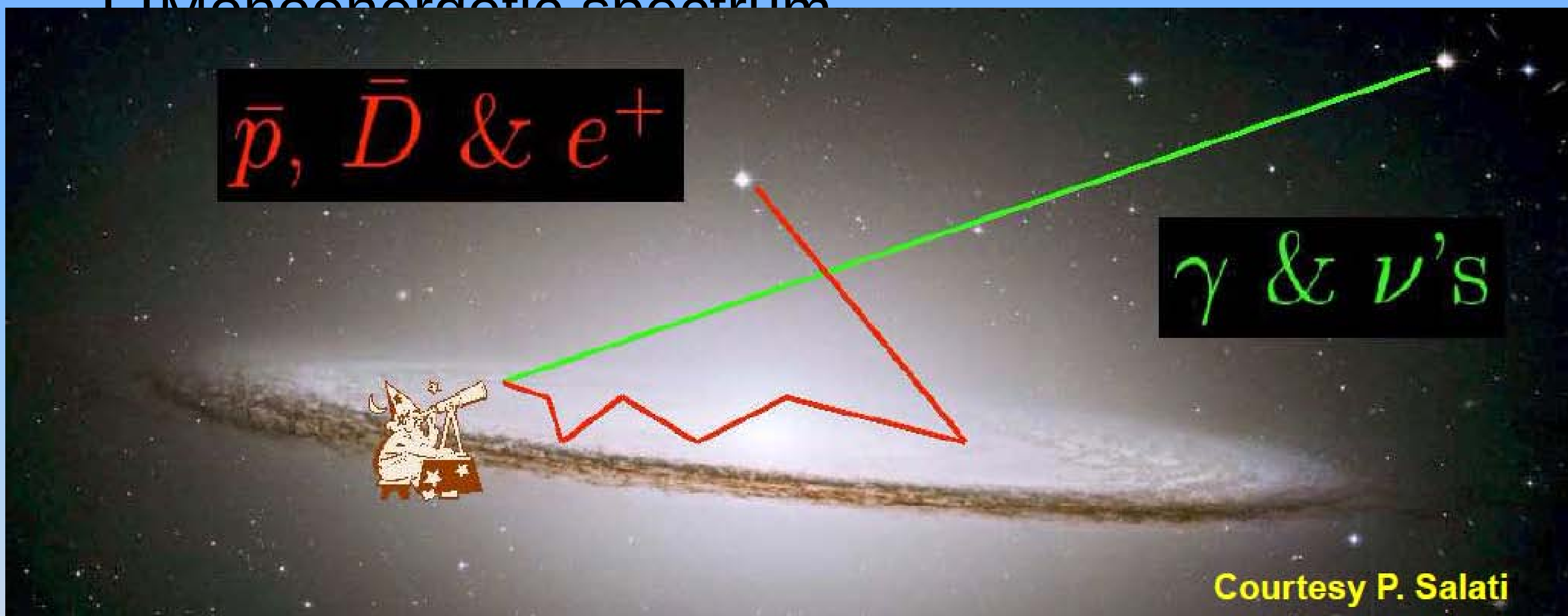
SPACE: EGRET, GLAST, PAMELA, INTEGRAL, AGILE, AMS-2…



γ
CR
ν

Indirect detection of dark matter -- Gamma rays

- Monoenergetic spectrum



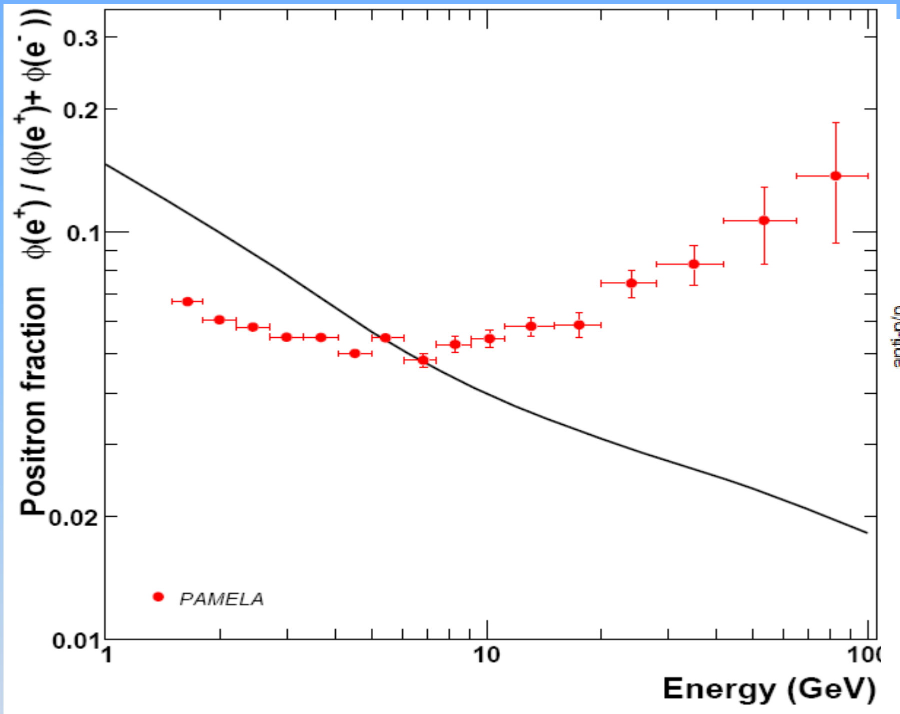
$$\chi\chi \to \cdots \to \pi^0 \to \gamma\gamma$$

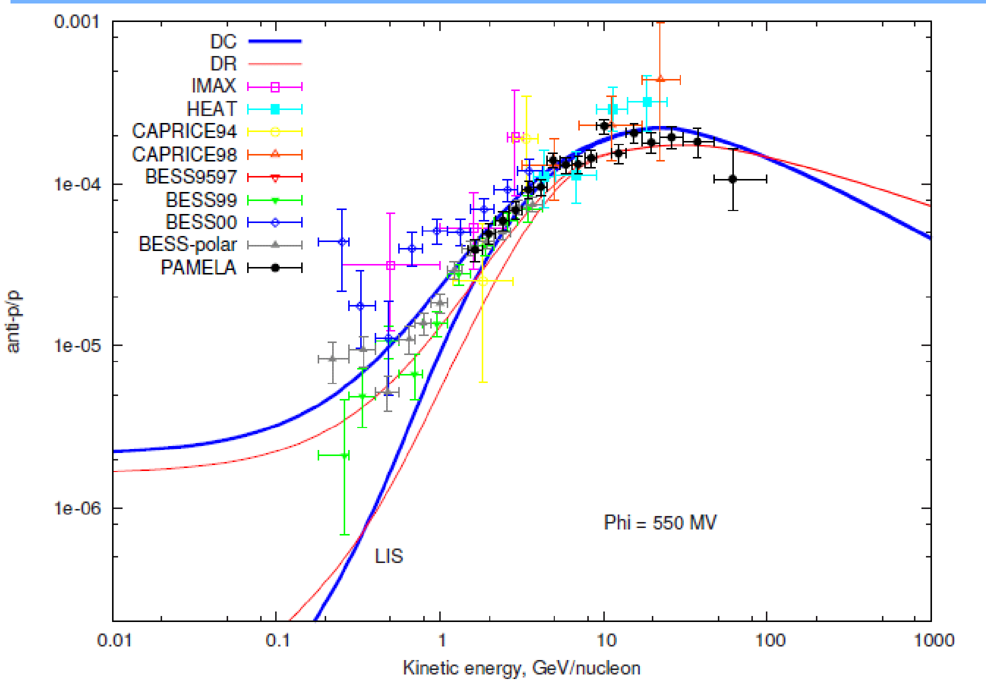
Flux is large, not definitive signal

PAMELA results of antiparticles in cosmic rays

Positron fraction

Antiproton fraction





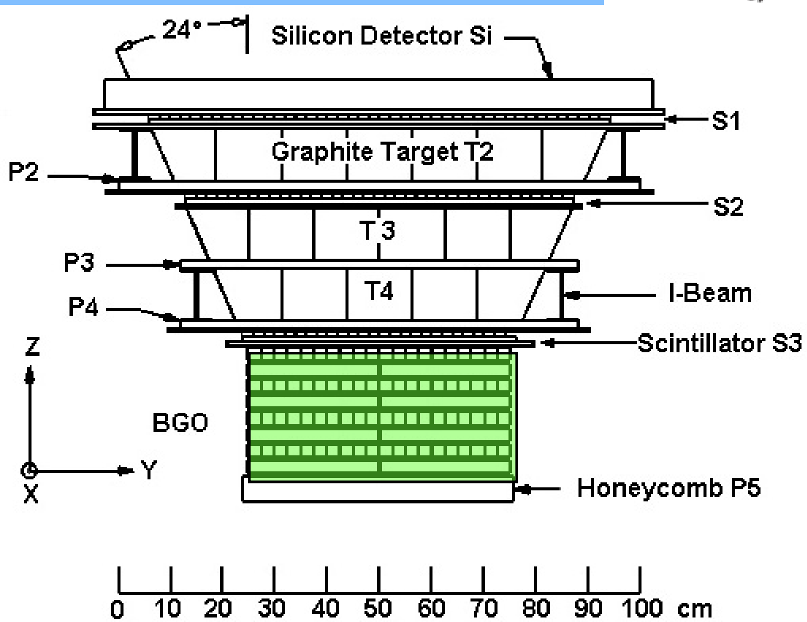
Nature 458, 607 (2009)

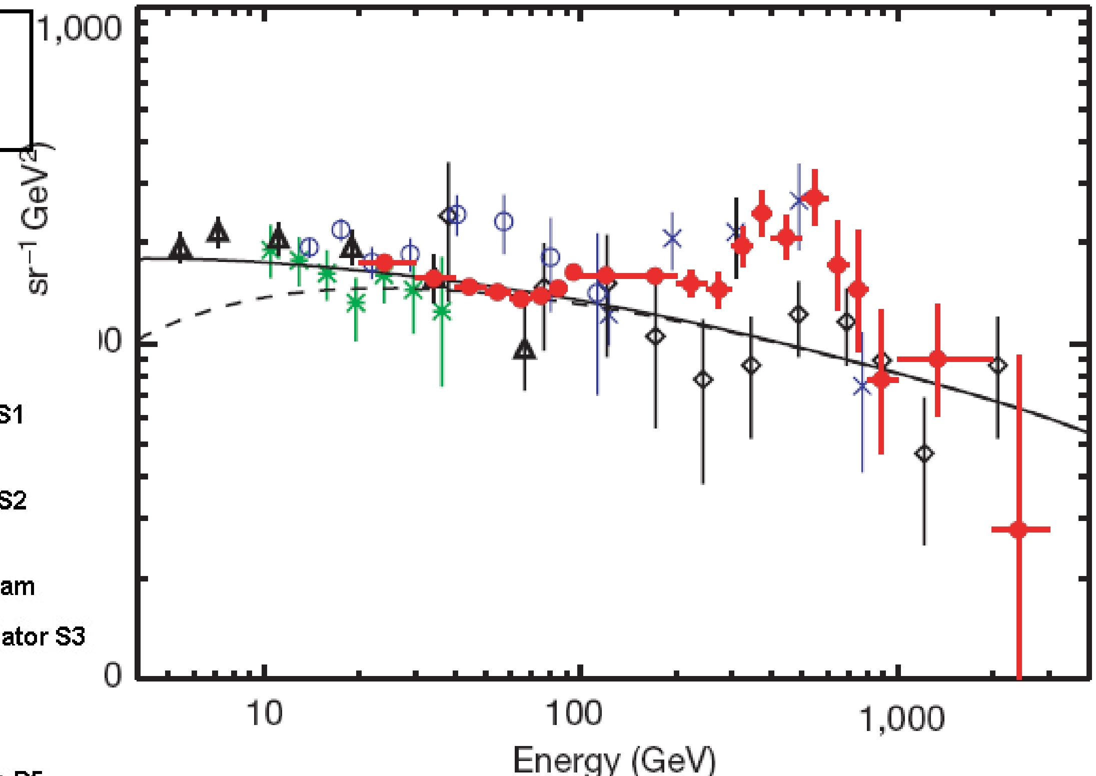
Phys.Rev.Lett.102:051101,2009

>700 citations after submitted on 28th Oct. 2008

Bump at the electron/positron spectrum

Chang et al.
Nature456, 362 2008

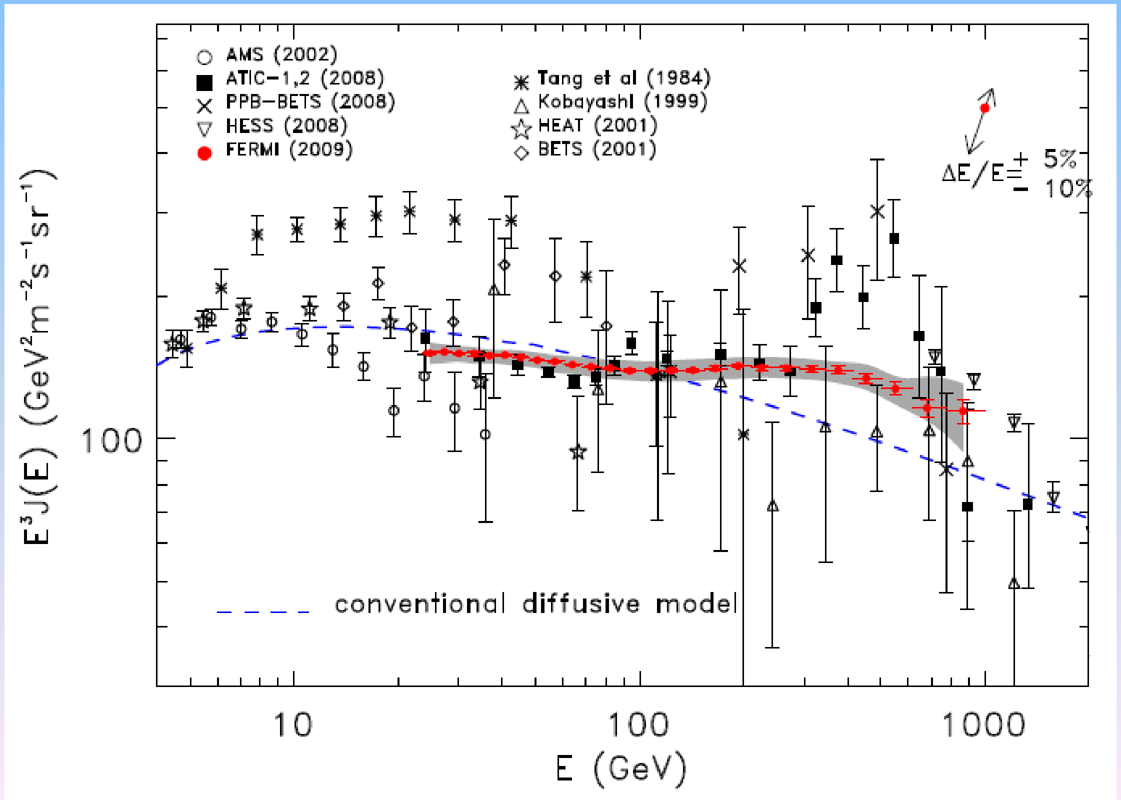




ATIC results showing agreement with previous data at lower energy and with the imaging calorimeter PPB-BETS at higher energy. The electron differential energy spectrum measured by ATIC (scaled by E^3) at the top of the atmosphere (red filled circles) is compared with previous observations from the Alpha Magnetic Spectrometer AMS (green stars)[31], HEAT (open black triangles)[30], BETS (open blue circles)[32], PPB-BETS (blue crosses)[16] and emulsion chambers (black open diamonds)[4,8,9], with one sigma uncertainties. The GALPROP code calculates a power-law spectral

Fermi results

- Fermi gives softer spectrum of (e+e-) than ATIC. Excess exists above the conventional model



怎么理解实验观察到的超出呢？

Astrophysical sources	Exotic sources
Nearby SNRs, pulsars Propagation effects Early SN stage interaction of CRs ……	Dark matter annihilation Dark matter decay

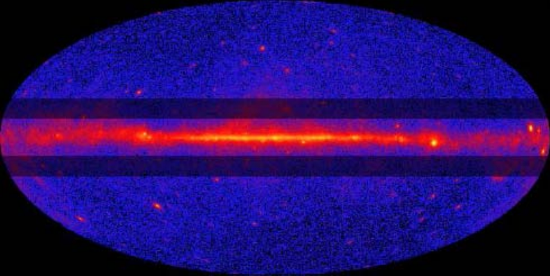
PAMELA数据得到暗物质的性质

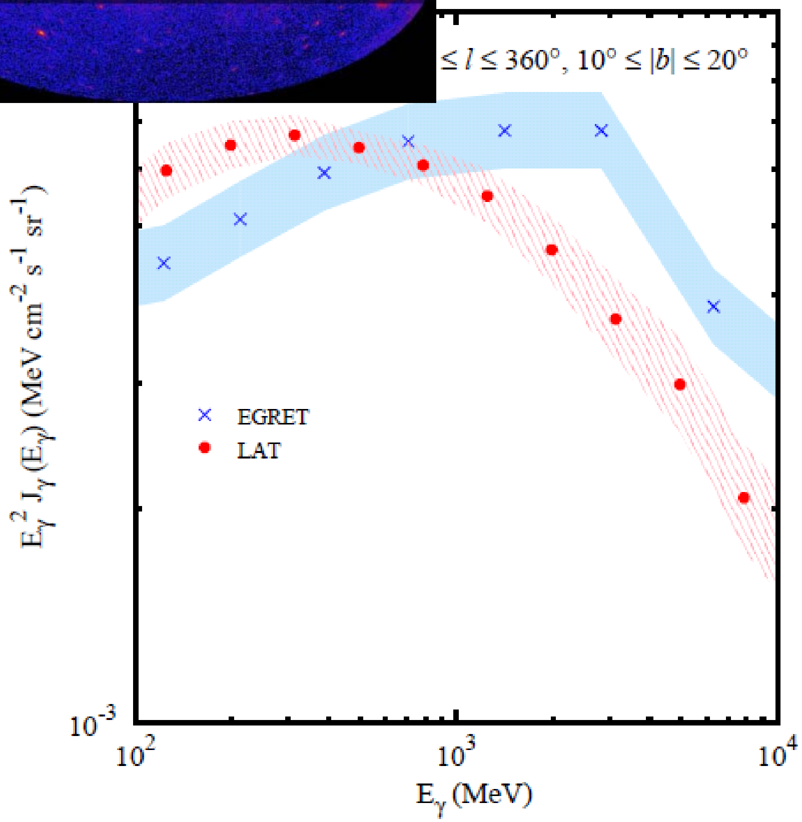
- 暗物质主要和轻子相互作用，而和夸克的相互作用比较微弱
- 要求暗物质相互作用很强，湮灭速率非常大；需要一些比较特别构建的模型
  - 1) nonthermal production
  - 2) Sommerfeld enhancement
  - 3) Breit-Wigner enhancement
  - 4) dark matter decay

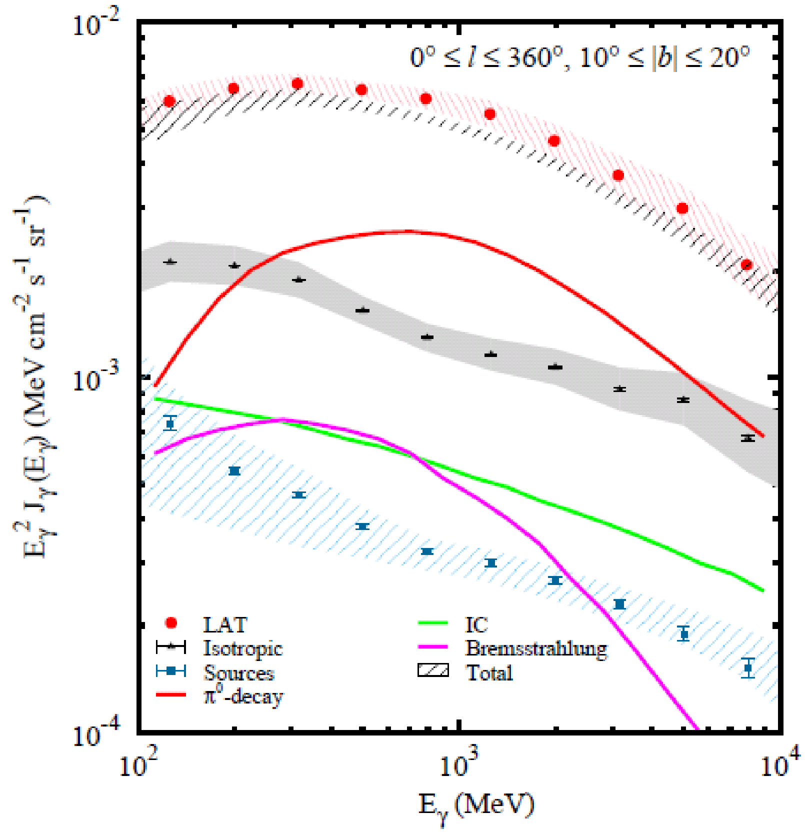
- 数据误差比较大，用天体物理起源和暗物质起源都可以给予解释

- ATIC、Fermi测量电子能谱不自洽，需要新的实验结果能够把能谱确定下来。

Fermi new results



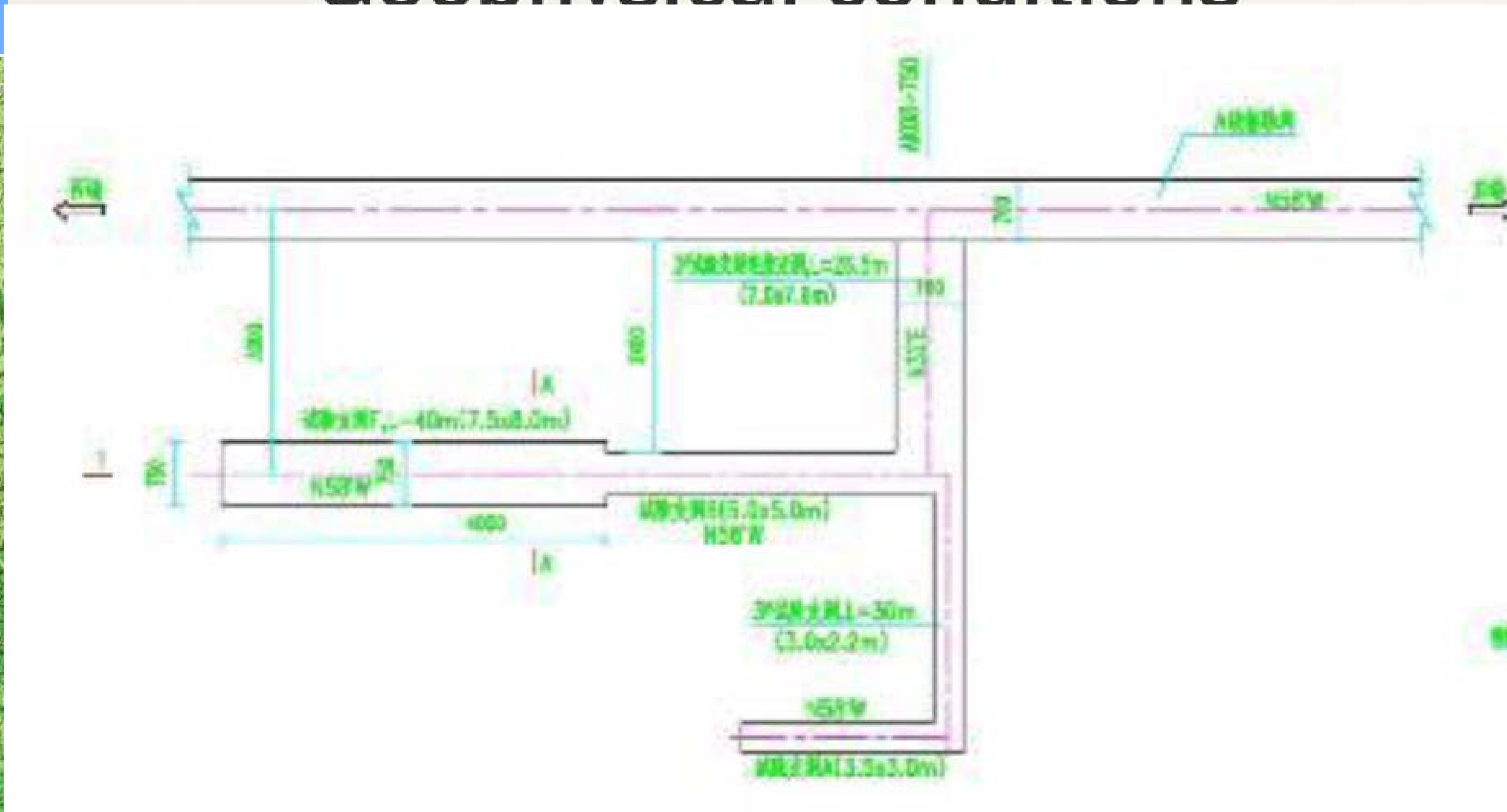




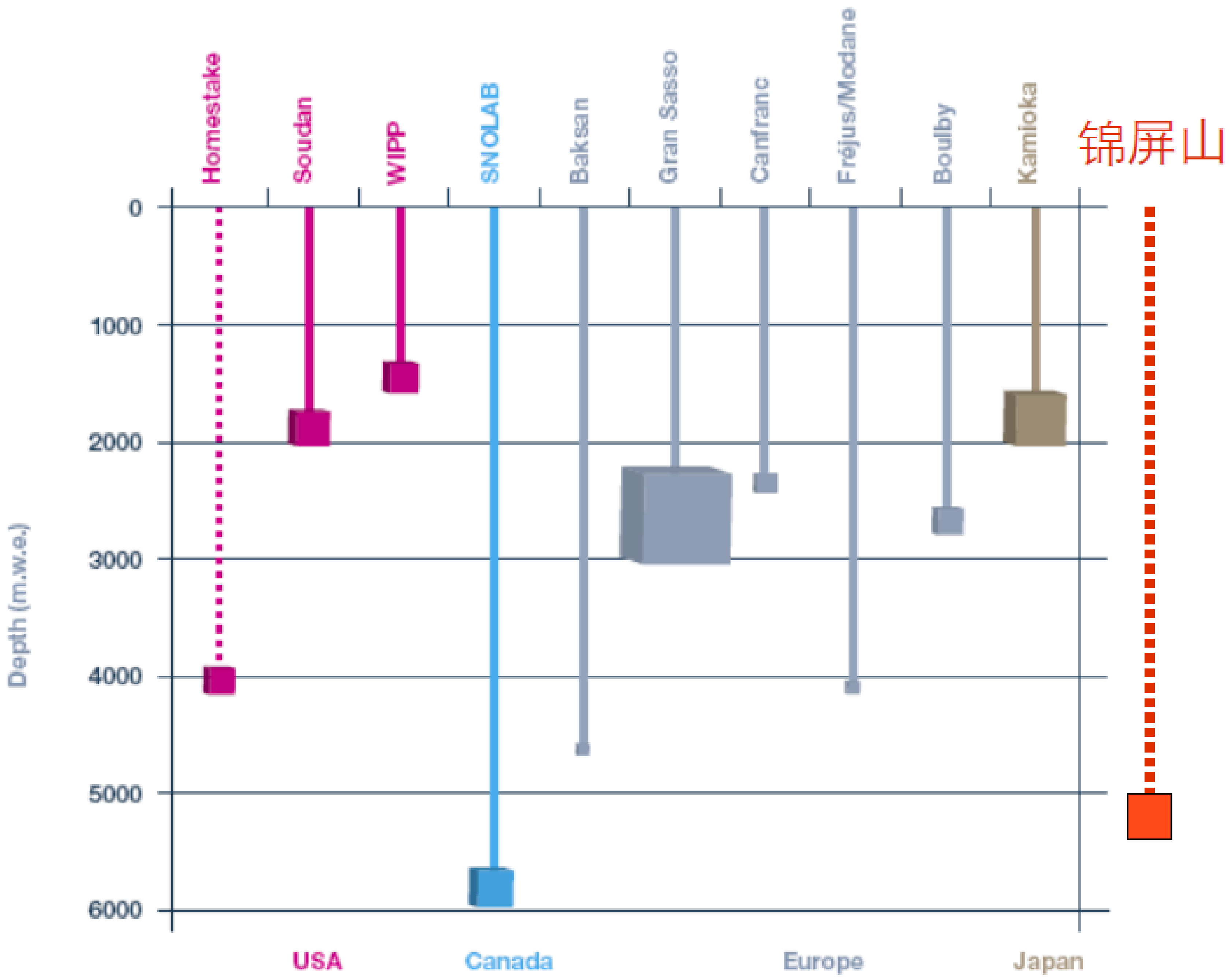
- 伽马射线观测能谱可以很好地被宇宙线预言结果拟合，说明CR和气体的相互作用等物理过程主导了伽马射线的辐射过程

- Fermi的观测没有发现新物理的迹象

Geophysical conditions



- Rock burst: mainly right after excavation
- Rich underground water: 5~7m^3/s, pressure 10MPa

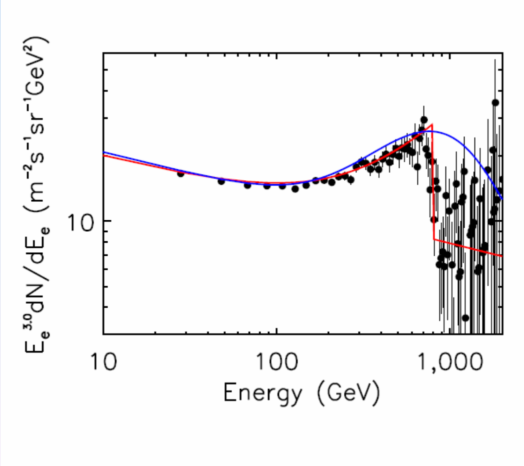


Homestake
Soudan
WIPP
SNOLAB
Baksan
Gran Sasso
Canfranc
Fréjus/Modane
Boulby
Kamioka
锦屏山
0
1000
2000
3000
4000
5000
6000
Depth (m.w.e.)
USA
Canada
Europe
Japan

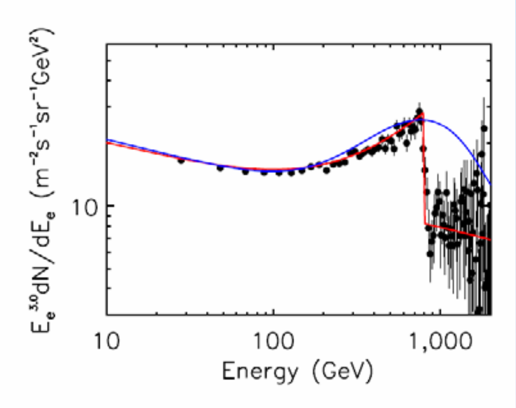
暗物质粒子卫星

- 探测器重量1200Kg（0.5m^2.sr，是ATIC的3倍）
- ATIC总共飞行48天，观测到330个电子（大于300GeV）
- 新探测器飞行60天，可以发现2000个电子（大于300GeV）
- 是世界上第一次在10GeV-10TeV能段对伽玛射线进行高分辨观测能量分辨

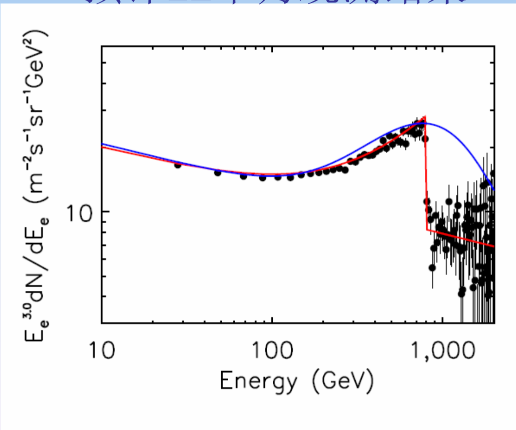
预计2个月观测结果



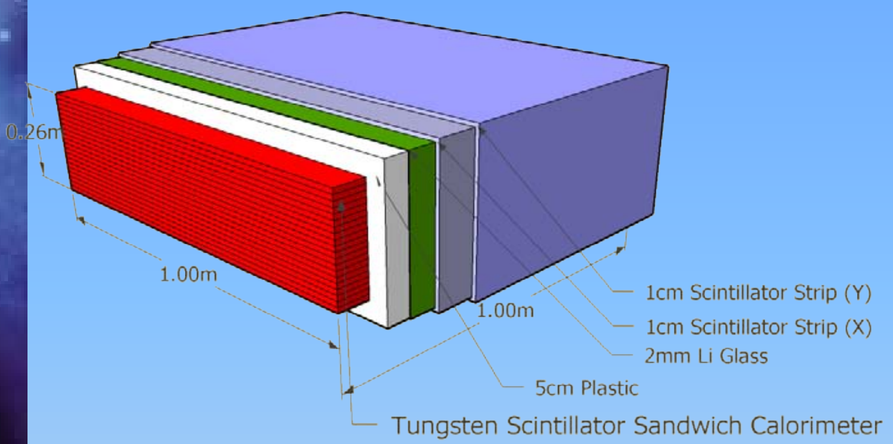
预计6个月观测结果

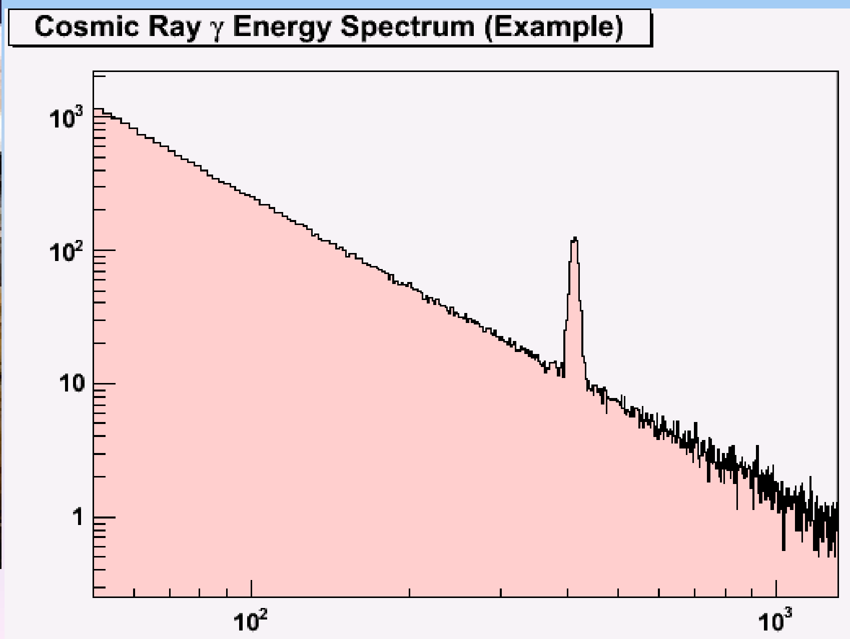


预计12个月观测结果

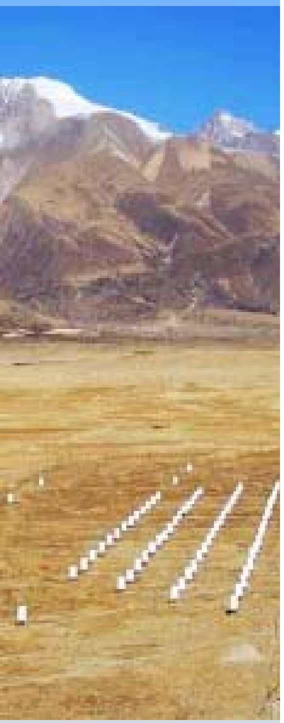


中国空间站 2018


0.26m
1.00m
1.00m
1cm Scintillator Strip (Y)
1cm Scintillator Strip (X)
2mm Li Glass
5cm Plastic
Tungsten Scintillator Sandwich Calorimeter


Cosmic Ray γ Energy Spectrum (Example)
10³
10²
10
1
10²
10³

ARGO & LHAASO @ Yangbajing



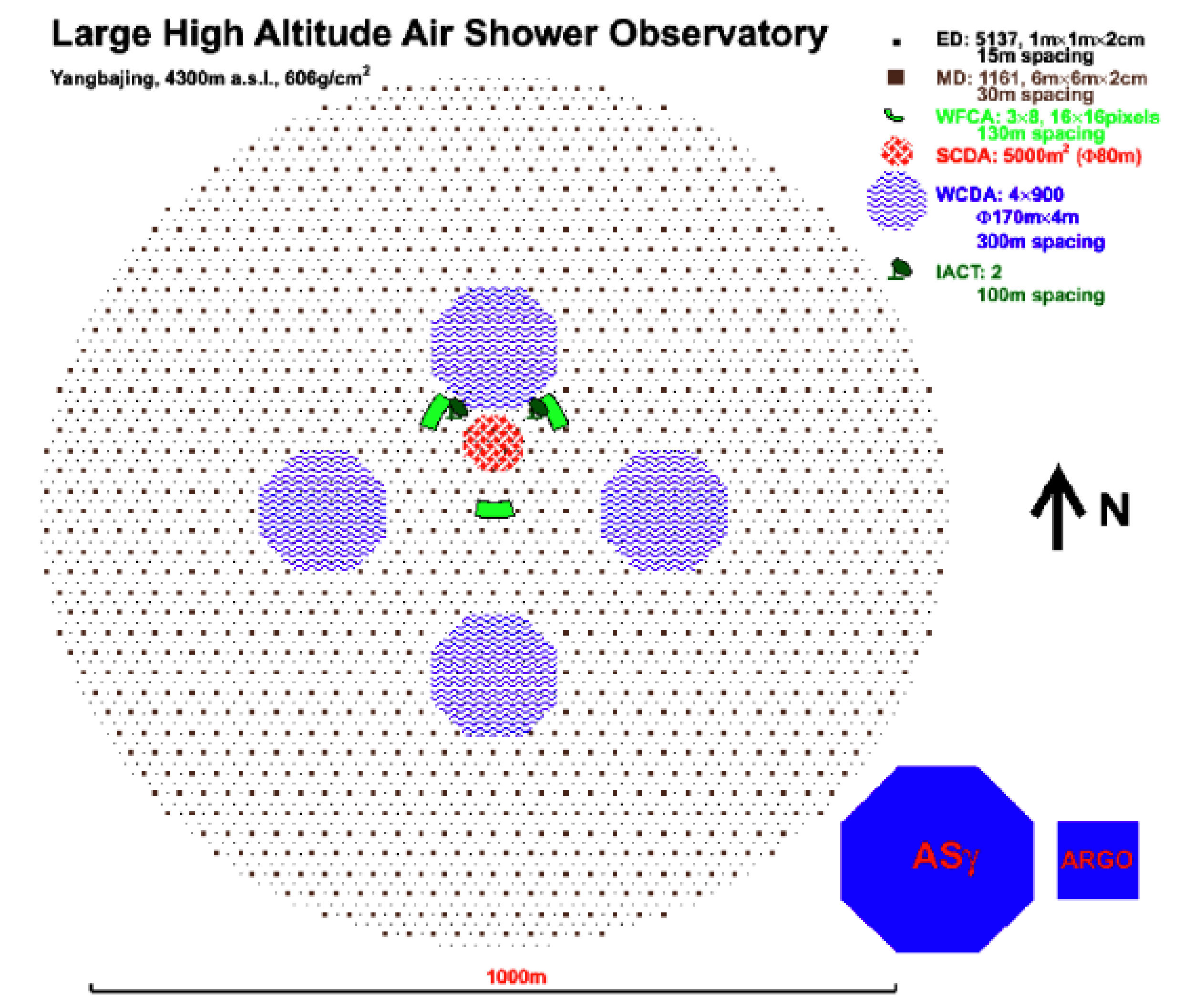
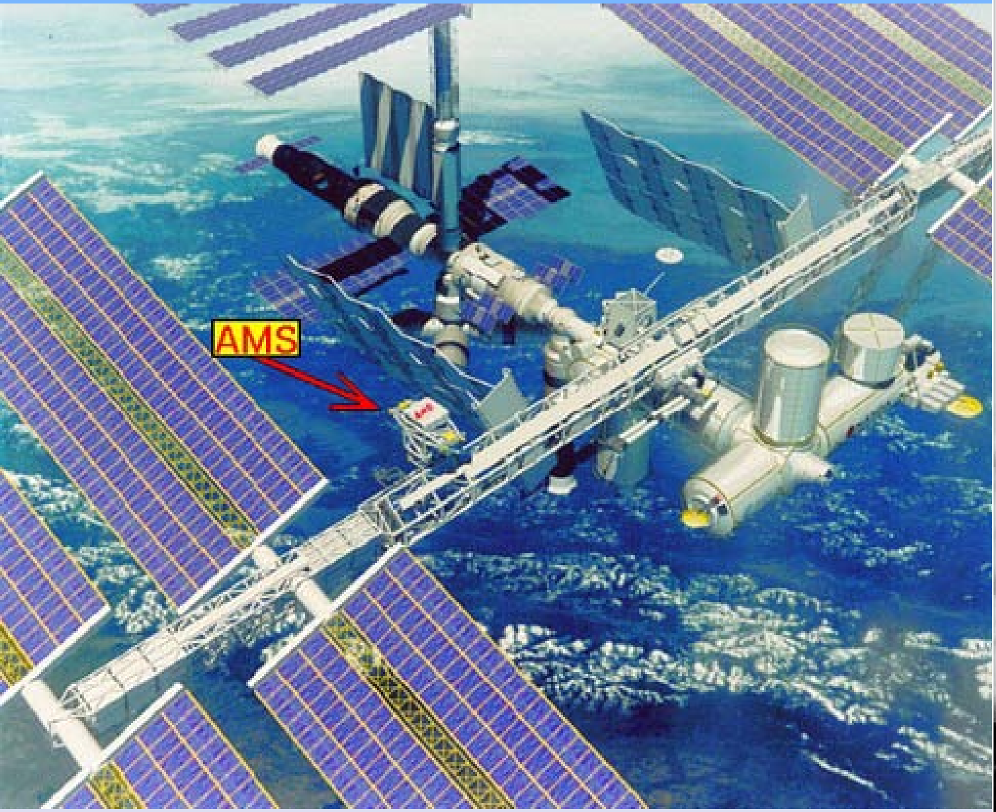
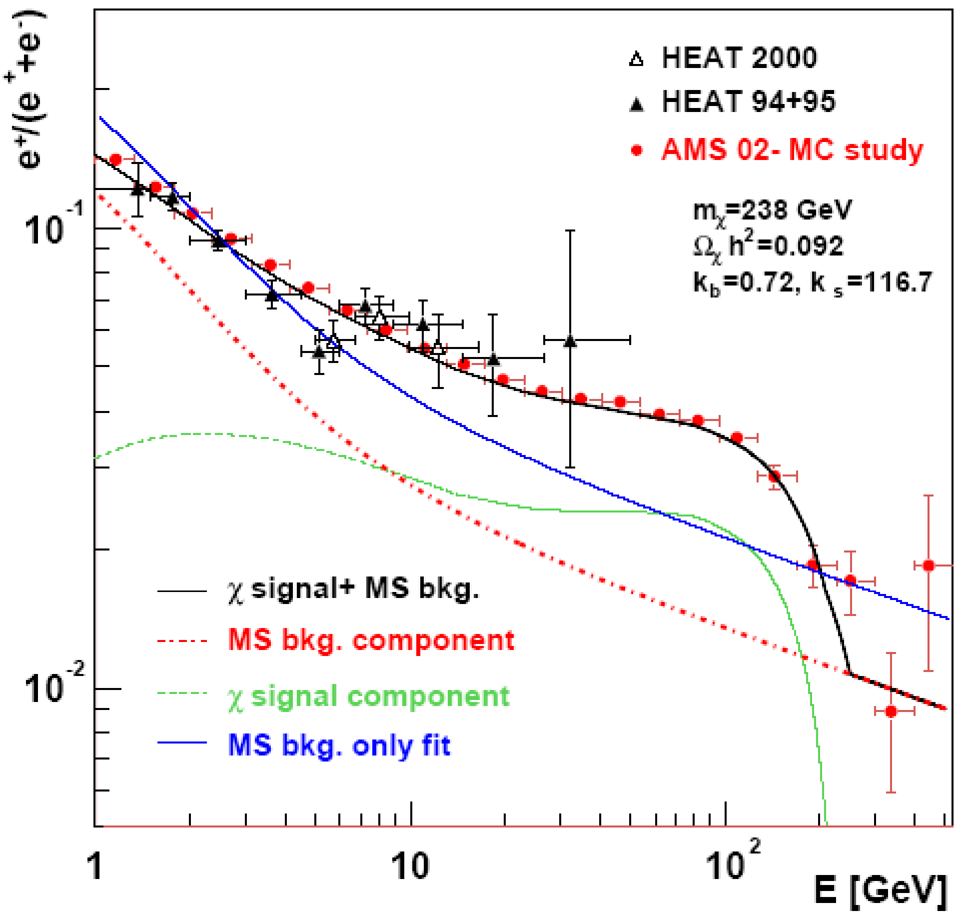


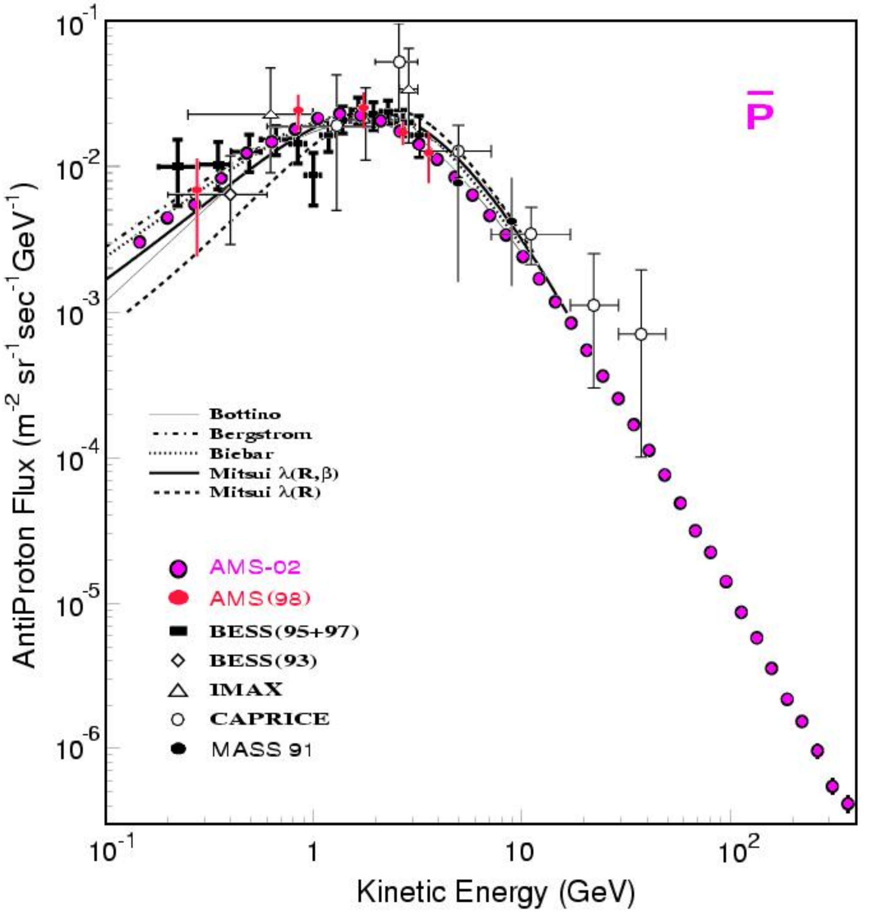
图 2-1 LHAASO 探测器布局图

AMS02





e+/(e++e-)
HEAT 2000
HEAT 94+95
AMS 02- MC study
mχ=238 GeV
Ωχ h2=0.092
kb=0.72, k s=116.7
χ signal+ MS bkg.
MS bkg. component
χ signal component
MS bkg. only fit
10-1
10-2
1
10
102
E [GeV]

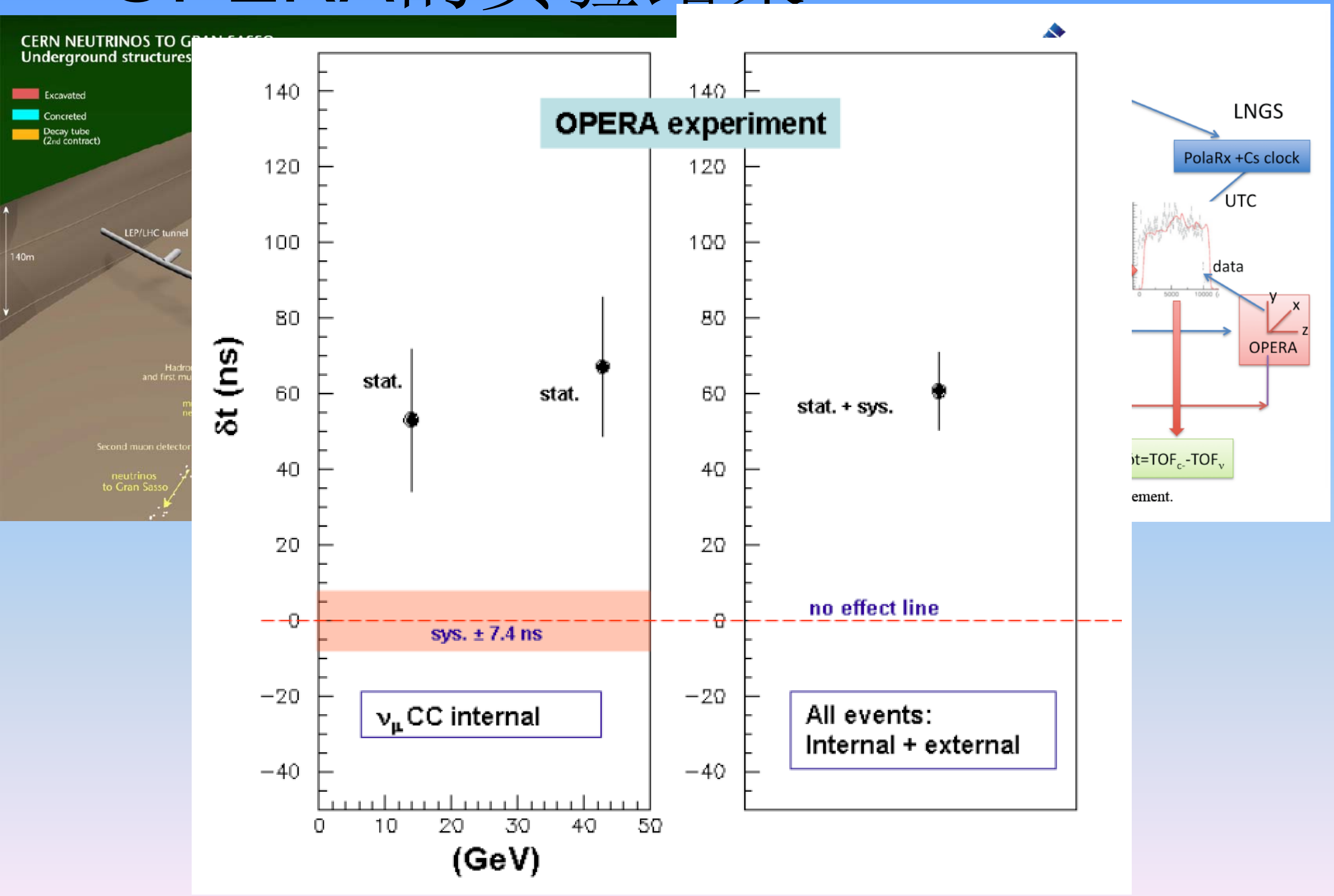


P̄
AntiProton Flux (m-2 sr-1sec-1GeV-1)
Kinetic Energy (GeV)
Bottino
Bergstrom
Biebar
Mitsui λ(R,β)
Mitsui λ(R)
AMS-02
AMS(98)
BESS(95+97)
BESS(93)
IMAX
CAPRICE
MASS 91
10-1
10-2
10-3
10-4
10-5
10-6
1
10
102

总结

- 基于对撞机实验，我们对于物质基本结构的认识有了本质的飞跃，建立了标准模型。
- 暗物质是宇宙早期产生的、超过目前对撞机能力的一种人类未曾认识的粒子。对暗物质的认识将意味着粒子物理的又一场革命。
- 无论暗物质直接探测还是间接探测实验在世界各国广泛开展，人们在为寻找暗物质正进行不懈的努力。结合LHC，人们期望很快能够找到暗物质的信号。

OPERA的实验结果



Underground structures
Excavated
Concreted
Decay tube
(2nd contract)
LEP/LHC tunnel
140m
Second muon detector
neutrinos
to Gran Sasso
OPERA experiment
δt (ns)
stat.
stat.
stat. + sys.
no effect line
sys. ± 7.4 ns
ν_μ CC internal
All events:
Internal + external
(GeV)
LNGS
PolaRx +Cs clock
UTC
data
OPERA
y
x
z

OPERA

Data summary

$$\delta_{\nu\gamma} = (v_\nu - c)/c = (2.48 \pm 0.28(\text{stat.}) \pm 0.30(\text{sys.})) \times 10^{-5}$$

For average 17 GeV

$$\delta_{\nu\gamma} = (2.16 \pm 0.76 \pm 0.30) \times 10^{-5} \text{ for } \langle E \rangle = 13.9 \text{ GeV}$$

$\delta_{\nu\gamma} = (2.74 \pm 0.74 \pm$

MINOS

$\delta_{\nu\gamma} = (5.1 \pm 2.9) \times$

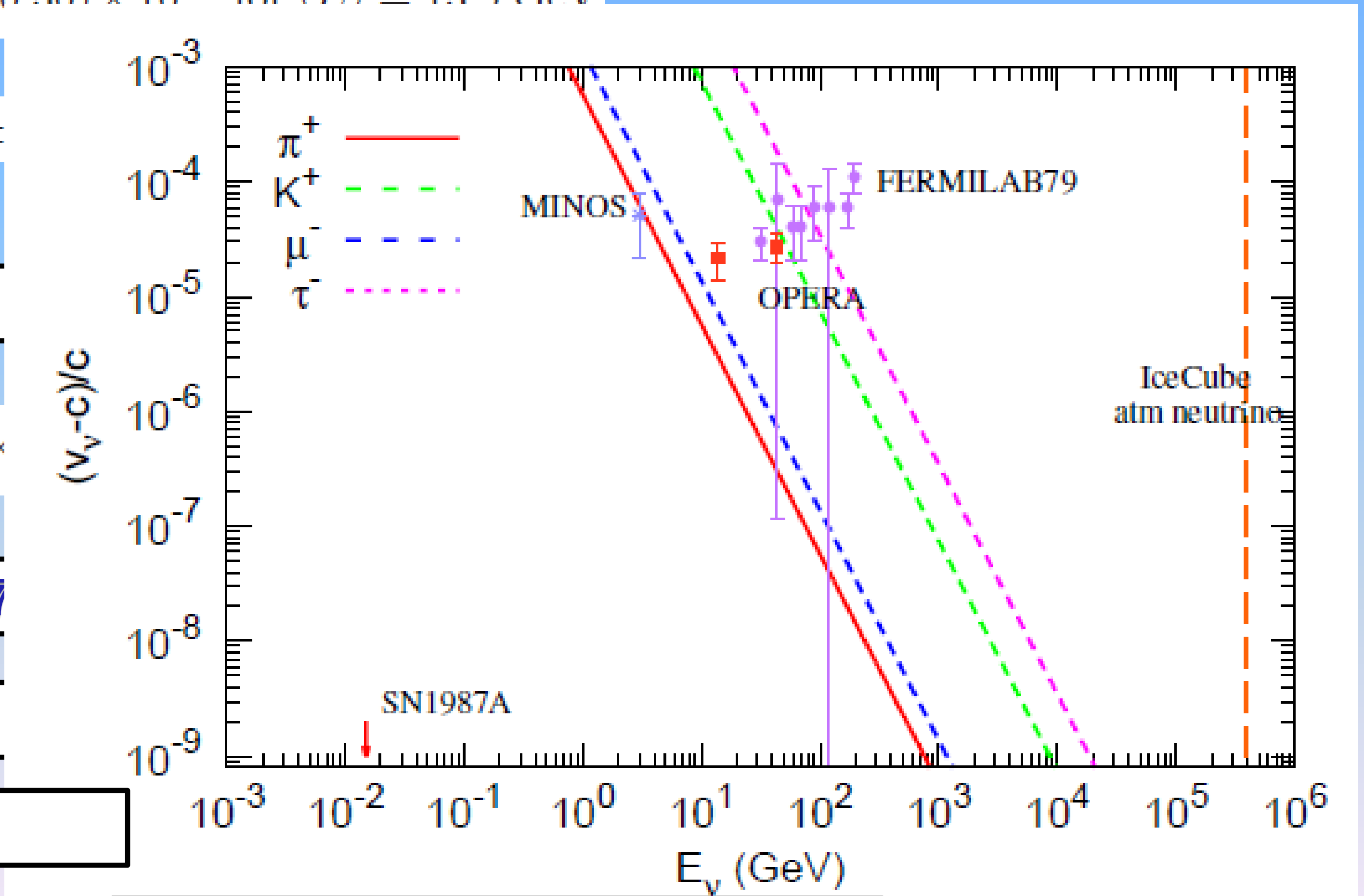
FERMILAB 197

$\delta \sim 10^{-5}$ For E ~

SN 1987A

$$\delta_{\nu\gamma} < 2 \times 10^{-9}$$

For E ~ tens MeV



The framework to understand

From the dispersion relation $E^2=m^2+p^2$, we get the group velocity $$v = \frac{\partial E}{\partial p} = 1 - \frac{m^2}{2p^2}$$

In order that v > 1, we have two options 1) m2 <0; 2) modify the dispersion relation

For the tachyon scenario, the lower energy its velocity is much bigger than 1. this scenario is ruled out by the SN1987A data.

For the second scenario, the Lorentz symmetry is broken perturbatively $E^2=m^2+p^2+\xi p^2$, with ξ is a small parameter. Then we get

$$v = \frac{\partial E}{\partial p} = 1 - \frac{m^2}{2p^2} + \frac{\xi}{2}$$

Take $\xi=5\times 10^{-5}$, we get the velocity is greater than 1 by 10^{-5}

Consequence of Lorentz invariance violation (LIV)

Many exotic processes will be induced by the superluminal neutrinos if it is interpreted at the LIV scenario, such as ν->ν+γ vaccum bremsstralung, ν->ν+e^++e^-(NC), ν-> μ+e+ν (CC). The NC process is discussed by Cohen and Glashow that shows for neutrinos energy greater than 12GeV, it loses energy too fast to be observed at Gran Sasso.

Besides the vaccum bremsstralung processes, we also considered the neutrino production process: π->μ+ν, μ->ν+ν+e. For superluminal neutrinos, these processes are forbidden for high energy neutrinos.

Constraints on superluminal neutrinos by neutrino energy ($E^2=m^2+p^2+\xi p^2$)

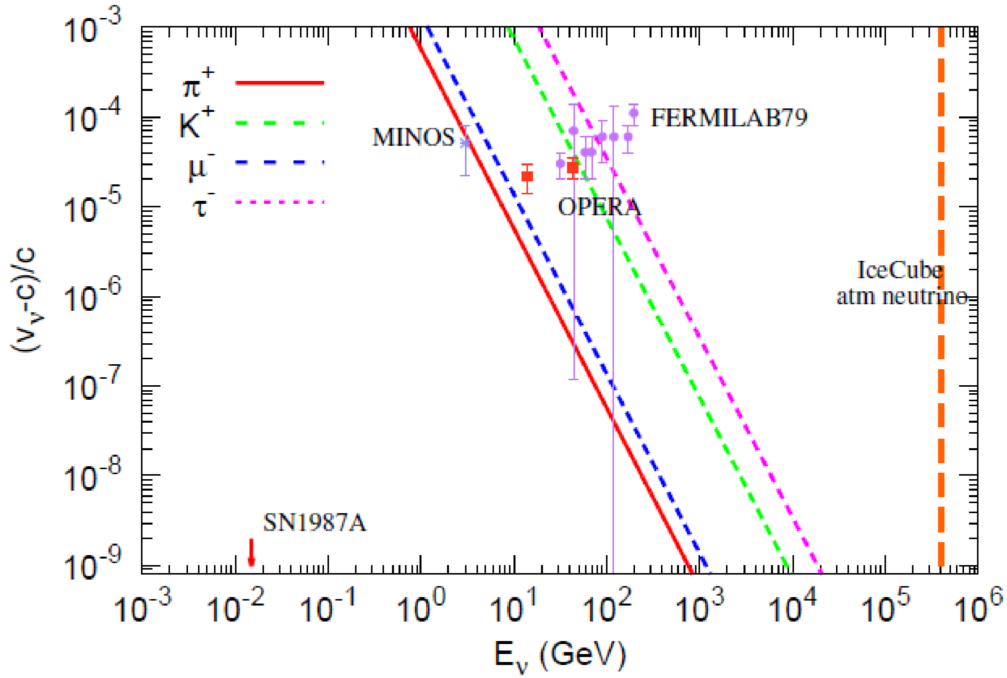


FIG. 1: The neutrino velocity constrained by the neutrino energy, for processes $\pi(K)^+ \to \mu^+\nu_\mu$, $\mu(\tau) \to \nu_{\mu(\tau)} + e(\mu) + \bar{\nu}_{e(\mu)}$.

Taking the OPERA face value of neutrino velocity, we have E < 5GeV.

$\delta_{\nu\gamma} < 3 \times 10^{-7}$ As 43 GeV neutrinos are observed at OPERA.

$\delta_{\nu\gamma} < 2 \times 10^{-8}$ As ~200 GeV neutrinos at FermiLab

Constraints on superluminal neutrinos by neutrino energy ($E^2 = m^2 + |\vec{p}|^2 + \beta|\vec{p}|^\alpha$)

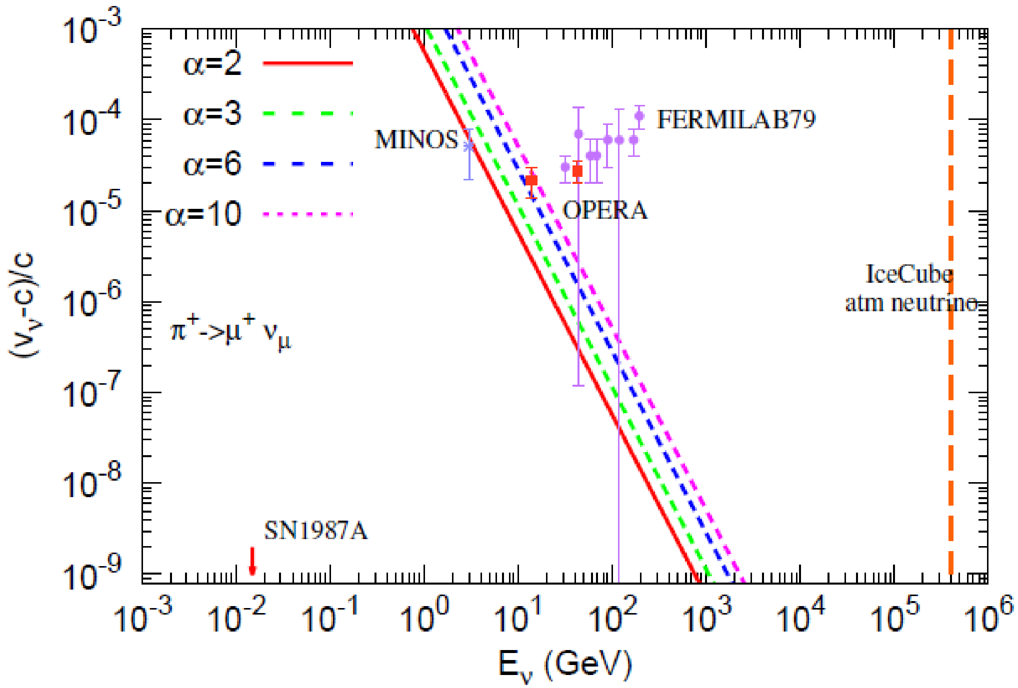


FIG. 2: The neutrino velocity constrained by the neutrino energy for the process $\pi^+ \to \mu^+\nu_\mu$, for different values of α.

More stringent constraints by atmospheric and astrophysical neutrinos

$\pi \to \mu + \nu_\mu$ and $\mu \to \nu_\mu + e + \nu_e$ can constrain the neutrino LIV parameter.

But the constraints depend on the accuracy of the LIV on π and μ. The process of Π->π+γ, μ->μ+γ, γ->μ+μ gives constrains on $\xi_\pi < 10^{-14}$ $|\xi_\mu| < 10^{-11}$

Therefore these process at most give constraint on the order of 10^{-11}. To get more stringent constraint we can consider the process $\nu_i \to \nu_j + \gamma$ $\nu_\mu \to \nu_\mu + e + e$

processes $e \to e\gamma$ and $\gamma \to ee$ give $|\xi_e| < 10^{-15}$

By calculating the three body decay of neutrinos we get the energy loss rate

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\langle \Delta E \rangle \Gamma \approx -10^{-3} \left(\frac{E}{\mathrm{TeV}}\right)^6 \left(\frac{\xi}{10^{-10}}\right)^3 \mathrm{GeV\ s^{-1}}$$

The energy rate will deform the neutrino spectrum. By comparing the neutrino spectrum we can get the constraint on the LIV parameter ξ. The spectrum become s

$$\phi(E) = \frac{q_0(E_0)}{4\pi d^2} \frac{\mathrm{d}E_0}{\mathrm{d}E},$$

$$\frac{\mathrm{d}E_0}{\mathrm{d}E} = \exp\left[\int_0^{t=d/c} \frac{\mathrm{d}b[E_0(t')]}{\mathrm{d}E_0(t')} \mathrm{d}t'\right]$$

Atmospheric neutrinos

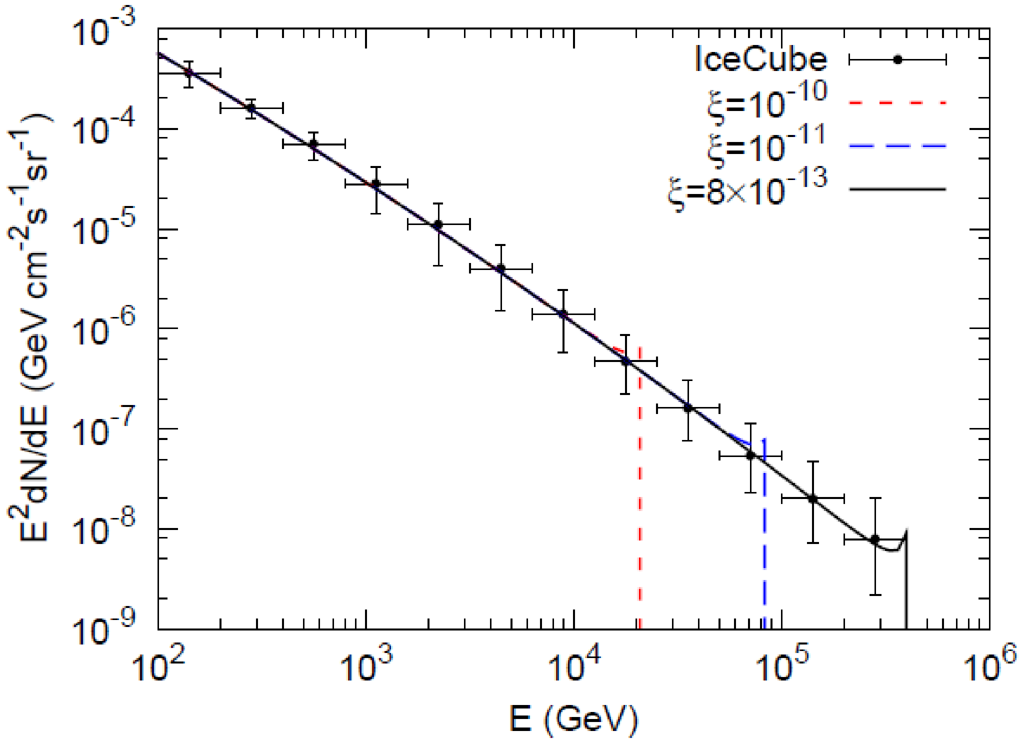


FIG. 3: The expected atmospheric neutrino spectra with LIV parameters $\xi = 10^{-10}$, 10^{-11} and 8×10^{-13} respectively. The measured data by IceCube is also plotted [27].

So, the IceCube observes neutrinos with energy up to 400TeV can constrain ξ to ~10^{-12}

By astrophysical neutrino sources, such as SNR neutrinos

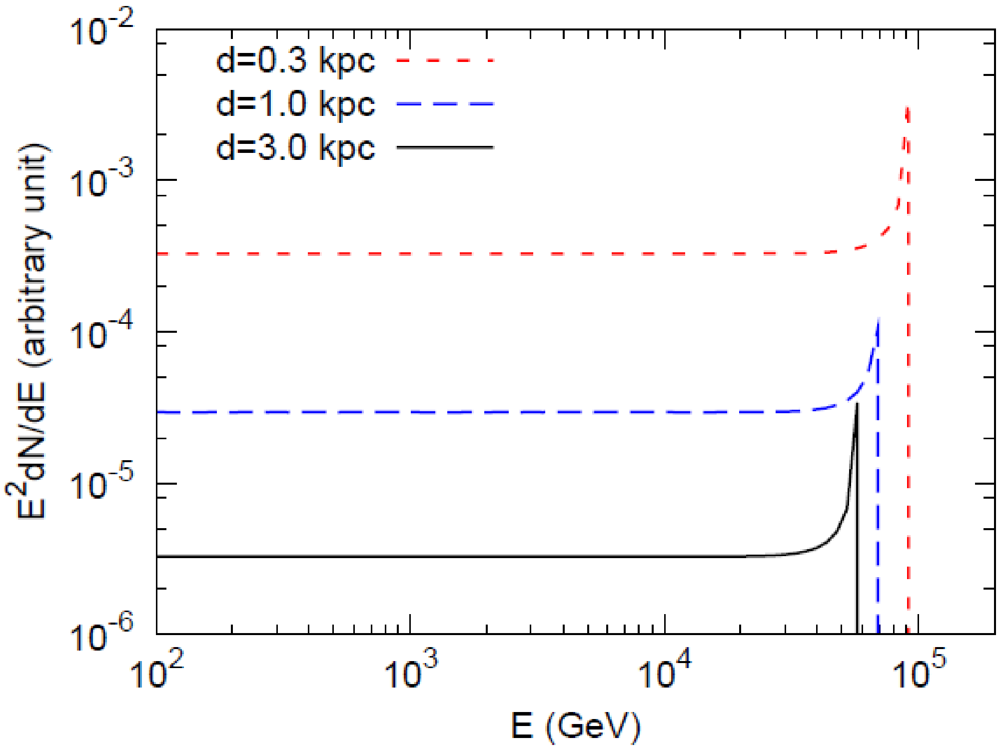


FIG. 4: Expected neutrino spectra with LIV parameter $\xi = 10^{-15}$, for sources at distances 0.3, 1.0 and 3.0 kpc respectively. The source spectrum is assumed to be proportional to E^{-2}.

Astrophysical neutrinos can probe even smaller LIV parameter, down to 10^{-15}

Summary

- OPERA observed superluminal neutrinos, while the possible systematic errors are still unknown.
- There many theoretical studies. Actually most models can be parametrized as a LIV dispersion relation of the neutrino sector.
- Our study shows that such LIV models are self-contradiction in explaining of the OPERA result. Same conclusions have been given by other studies.
- Is it possible from some phenomena which obey Lorentz symmetry? By quantum measurement, neutrino mixing?