# 暗物质

毕效军
中国科学院高能物理研究所

“2017 年理论物理前沿暑期讲习班——暗物质、
中微子与粒子物理前沿，
2017/7/24

# 课程大纲

- 暗物质简介
  - 存在证据、模型、热退耦、如何探测及最新进展
- 间接探测
  - 伽马、中微子信号计算 -- 暗物质分布模型/CDM的问题及一些新的模型
  - 带电粒子信号计算 – 宇宙线传播
- 直接探测
- 对撞机探测

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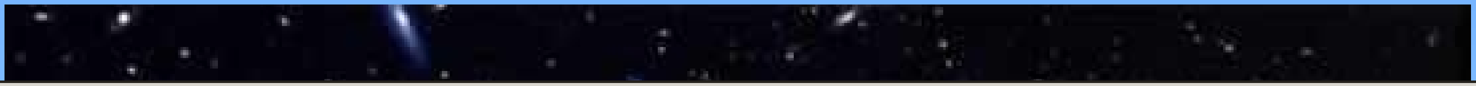
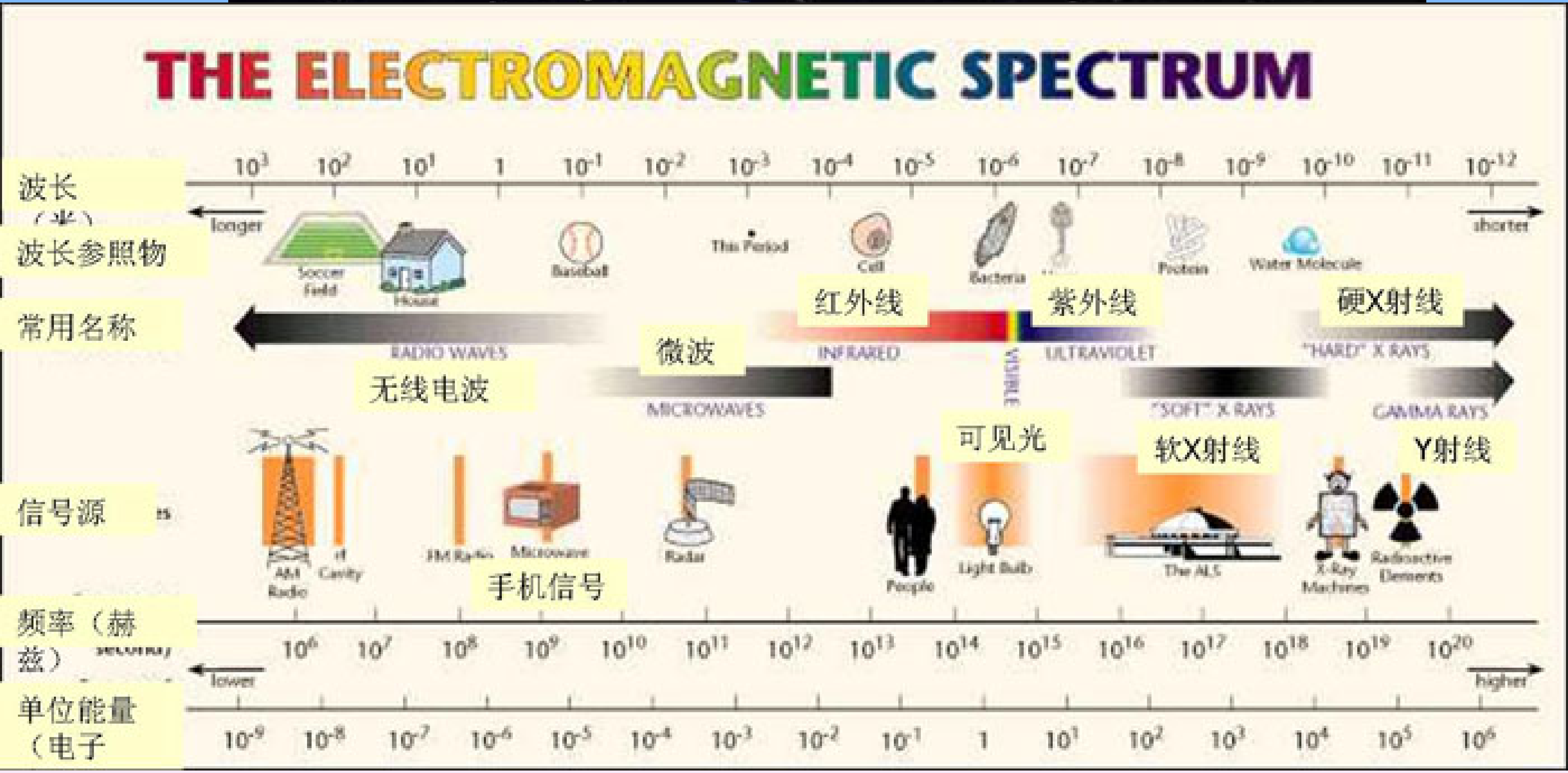
# 何为暗物质（dark matter）？





# 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).

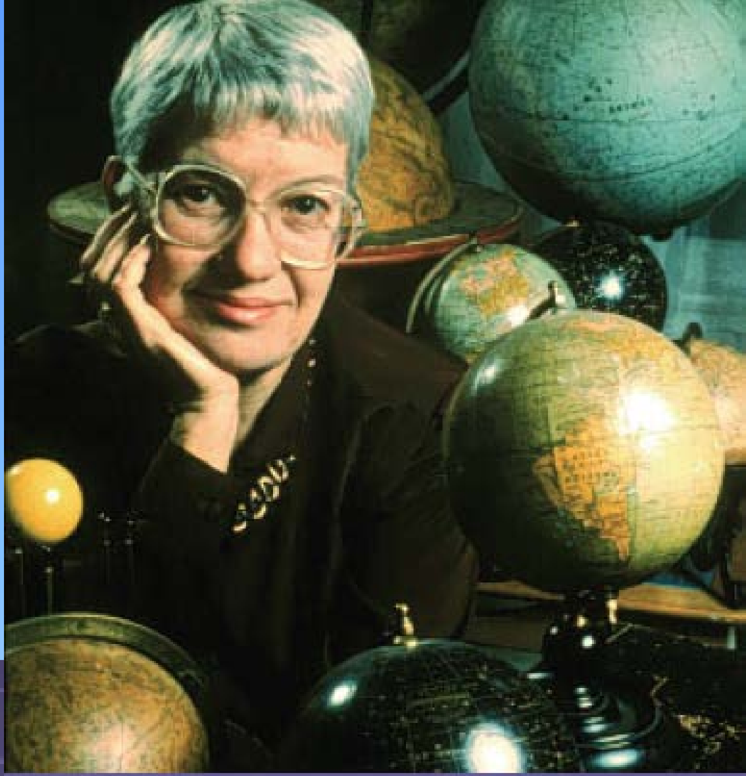
# Evidences — cluster scale

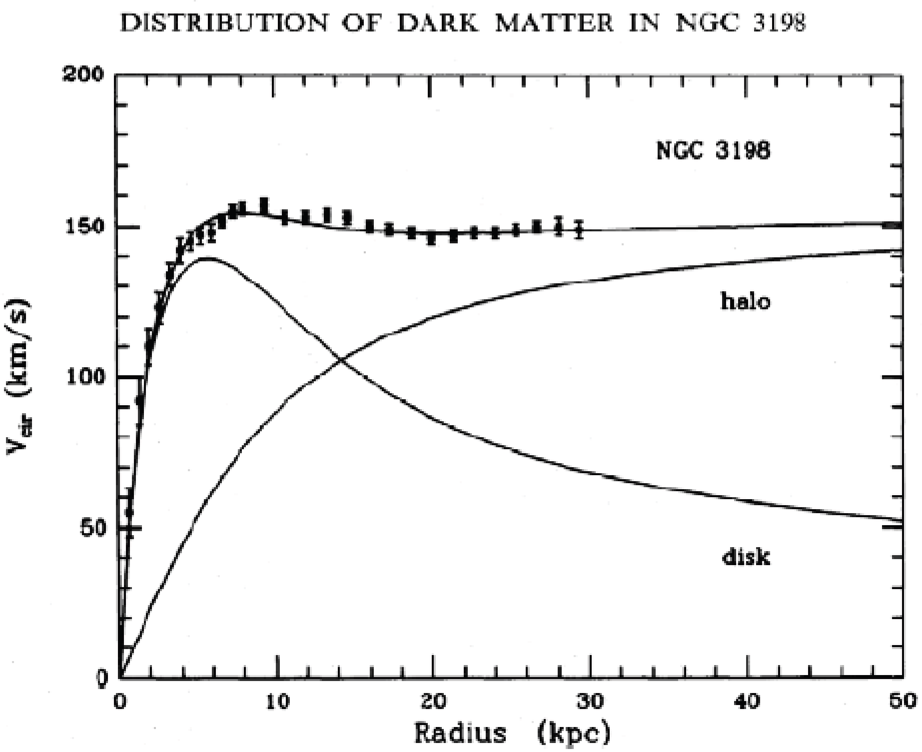
- 1933, Zwicky found the first evidence for the presence of dark matter in the Coma cluster.

A system at dynamical equilibrium obeys the virial theorem: K+U/2=0. Zwicky found that the kinetic term estimated by measuring the proper velocities of the individual galaxies was much larger than the potential term due to luminous galaxies: $M/L=300M_\odot/L_\odot$

Coma cluster

# Vera Rubin






OBSERVED:
FLAT ROTATION CURVE

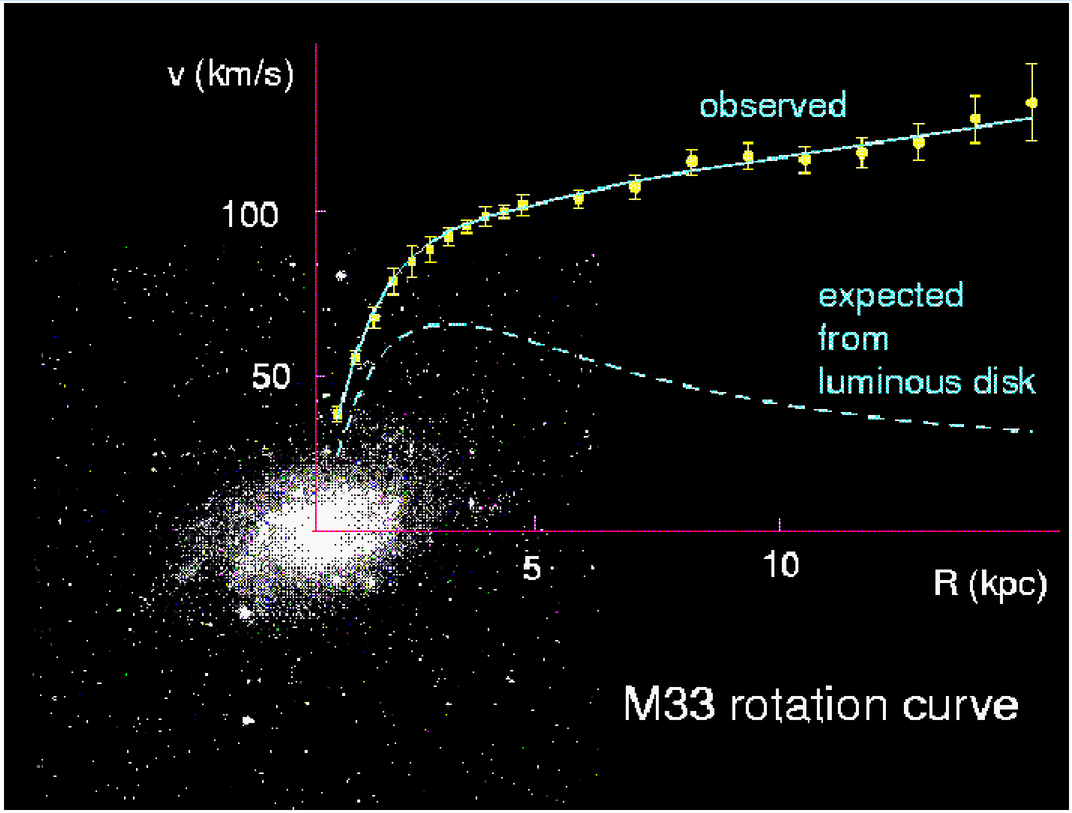
EXPECTED FROM STARS

# 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)

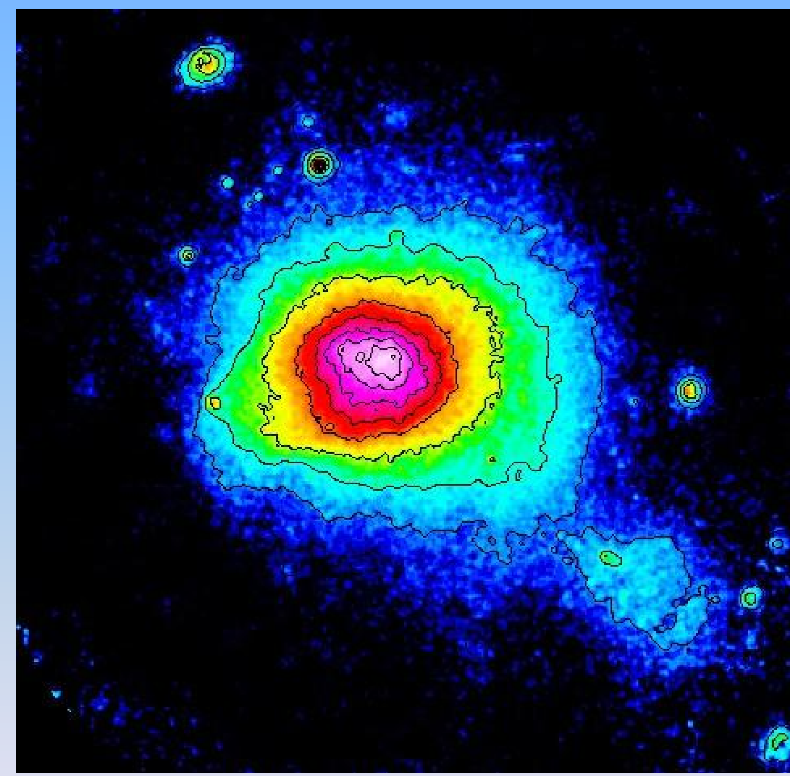


# Evidences — cluster scale (Mpc)

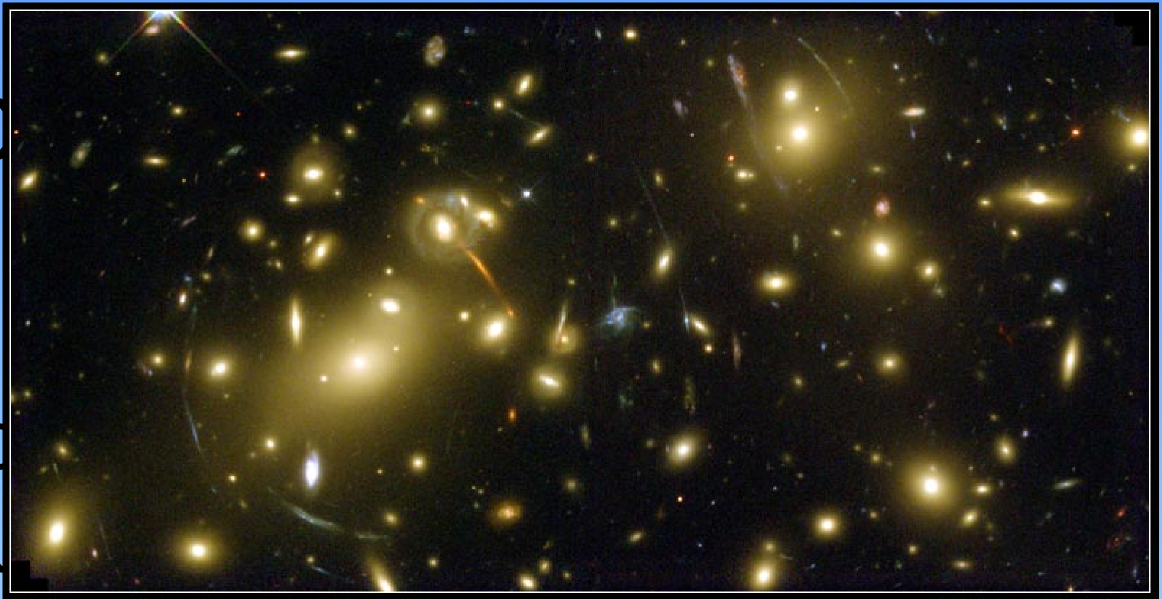
- Cluster contains hot gas which is at hydro static equilibrium. It's temperature follows,

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

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



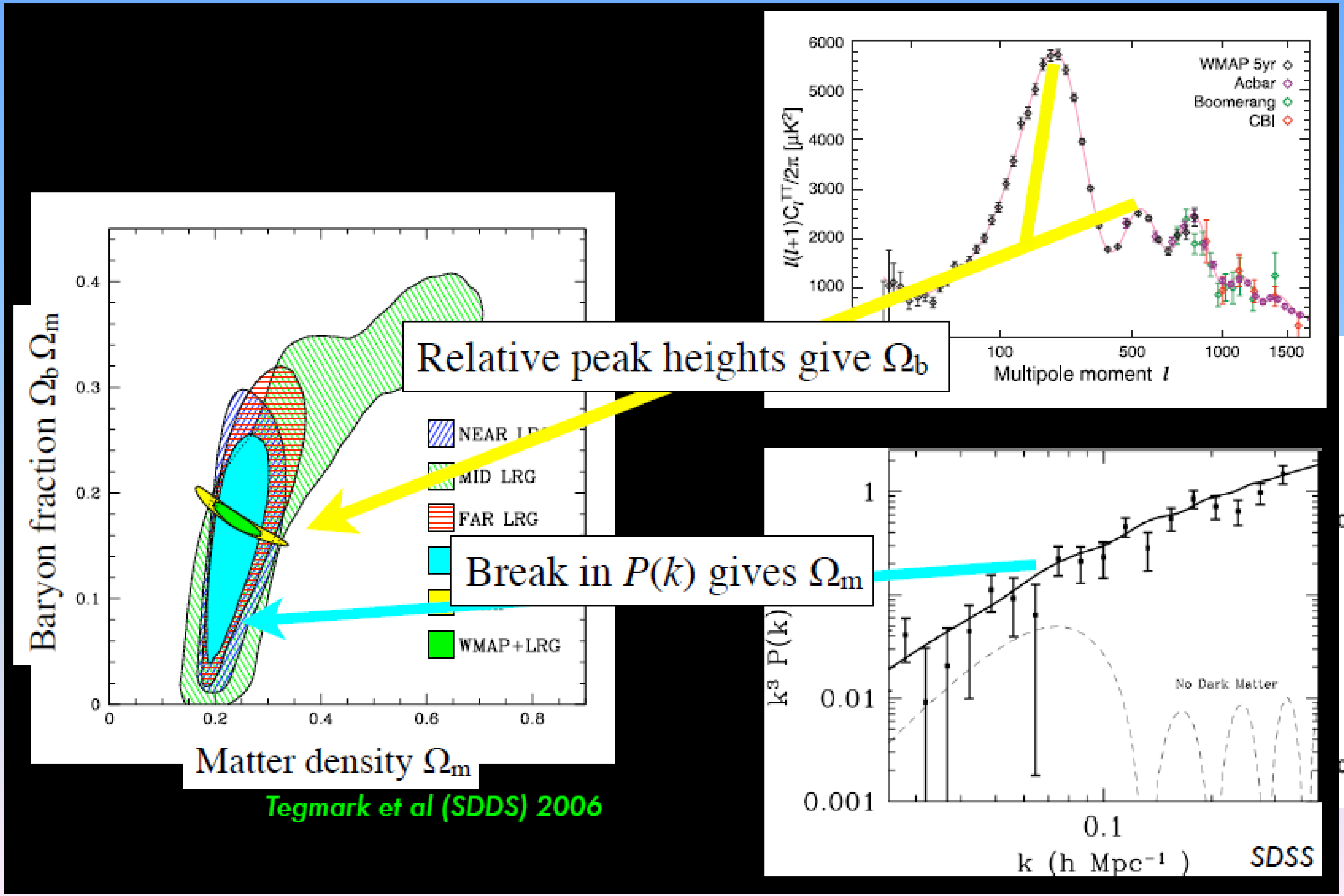
# Evidenc



Galaxy Cluster Abell 2218 HST • WFPC2
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

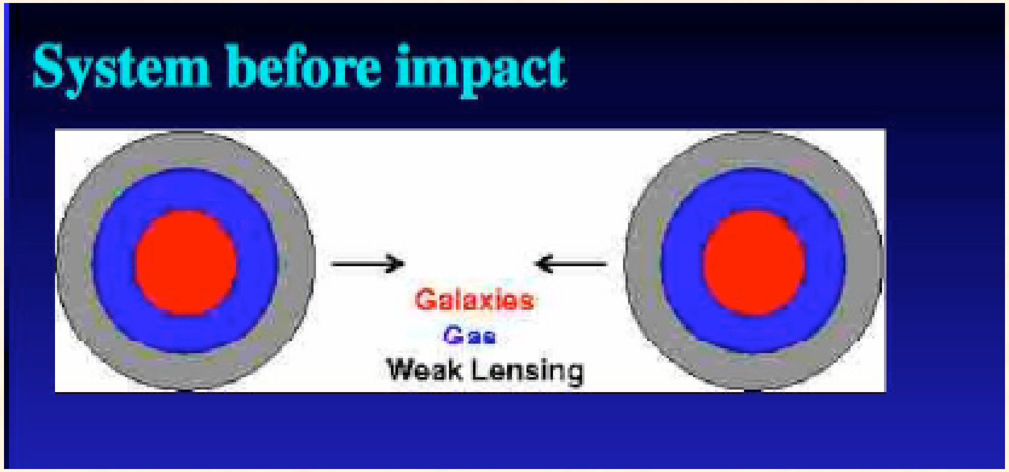
- Weak lensing images of bac foreground clu cluster mass.
- Sunyaev-Zeldovich distortion measures the distortion of CMB passing through cluster, which measure the temperature of the gas and therefore the mass of the cluster.
- …other measurements

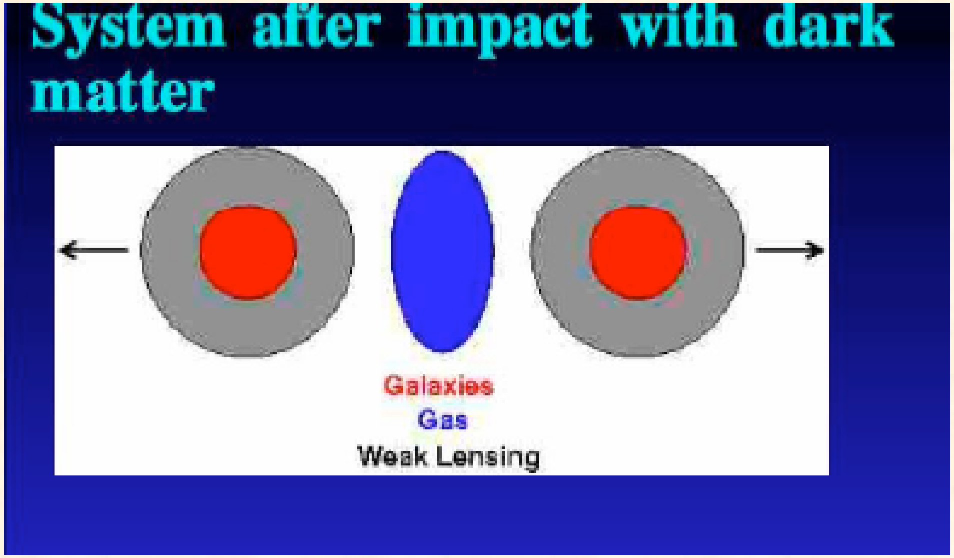
# Evidences — cosmological scale (Gpc)

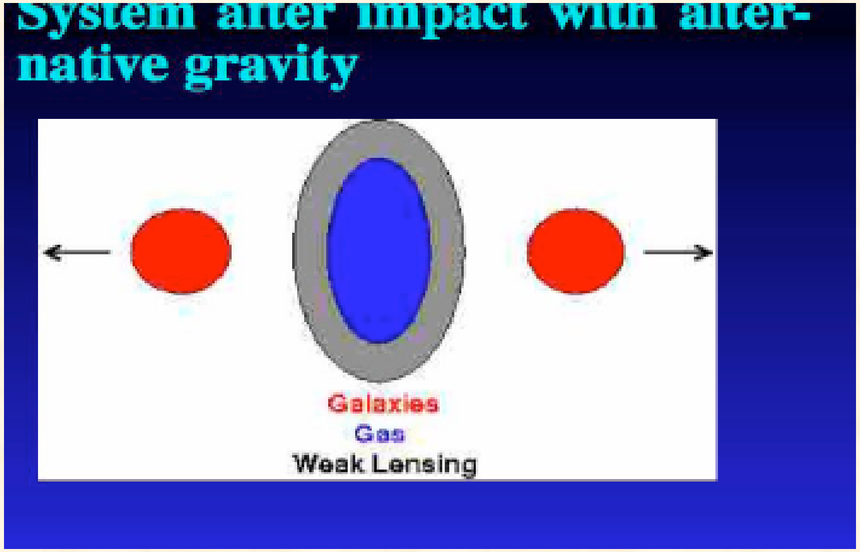


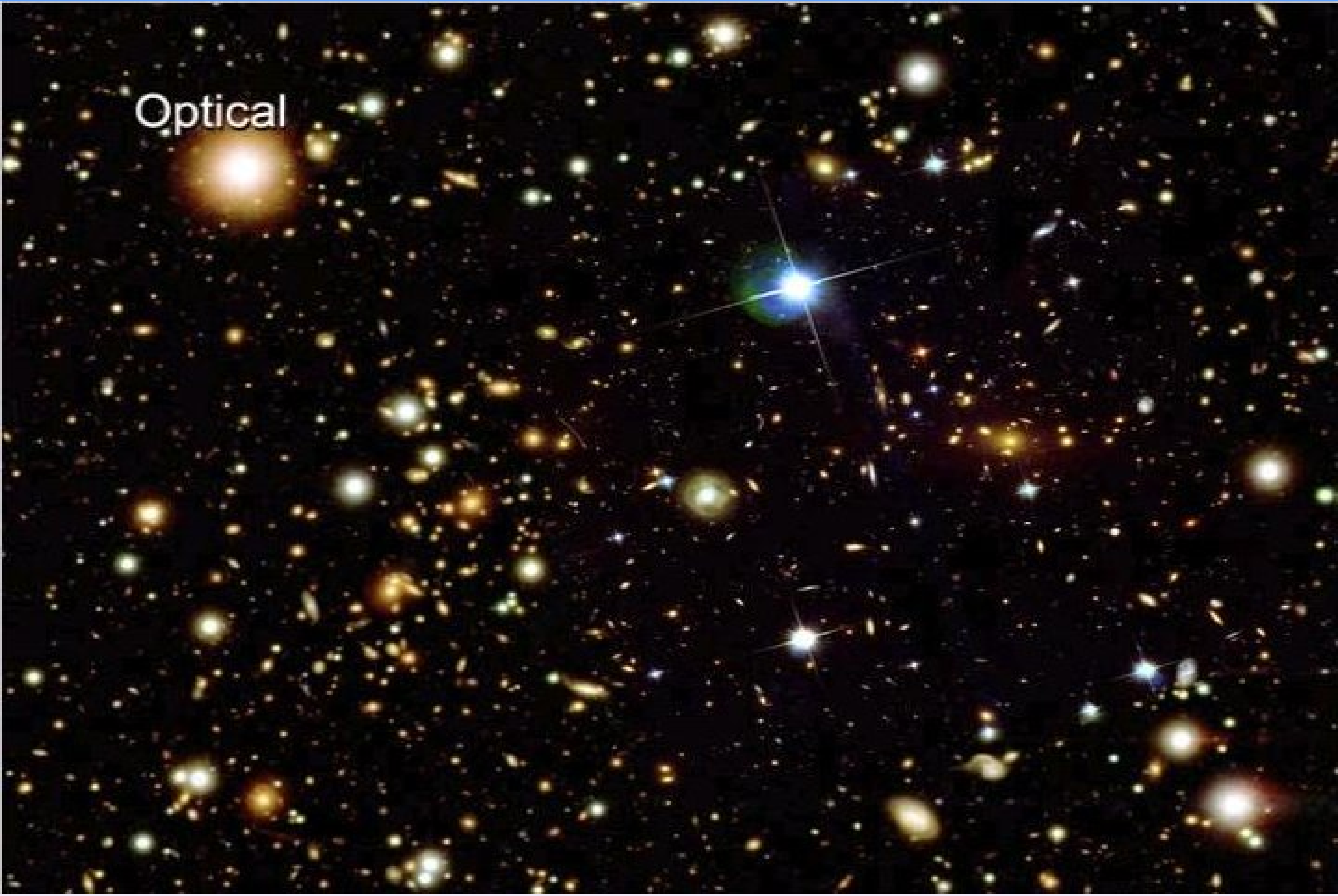
# Dark matter vs alternate gravity (MOND) : a test

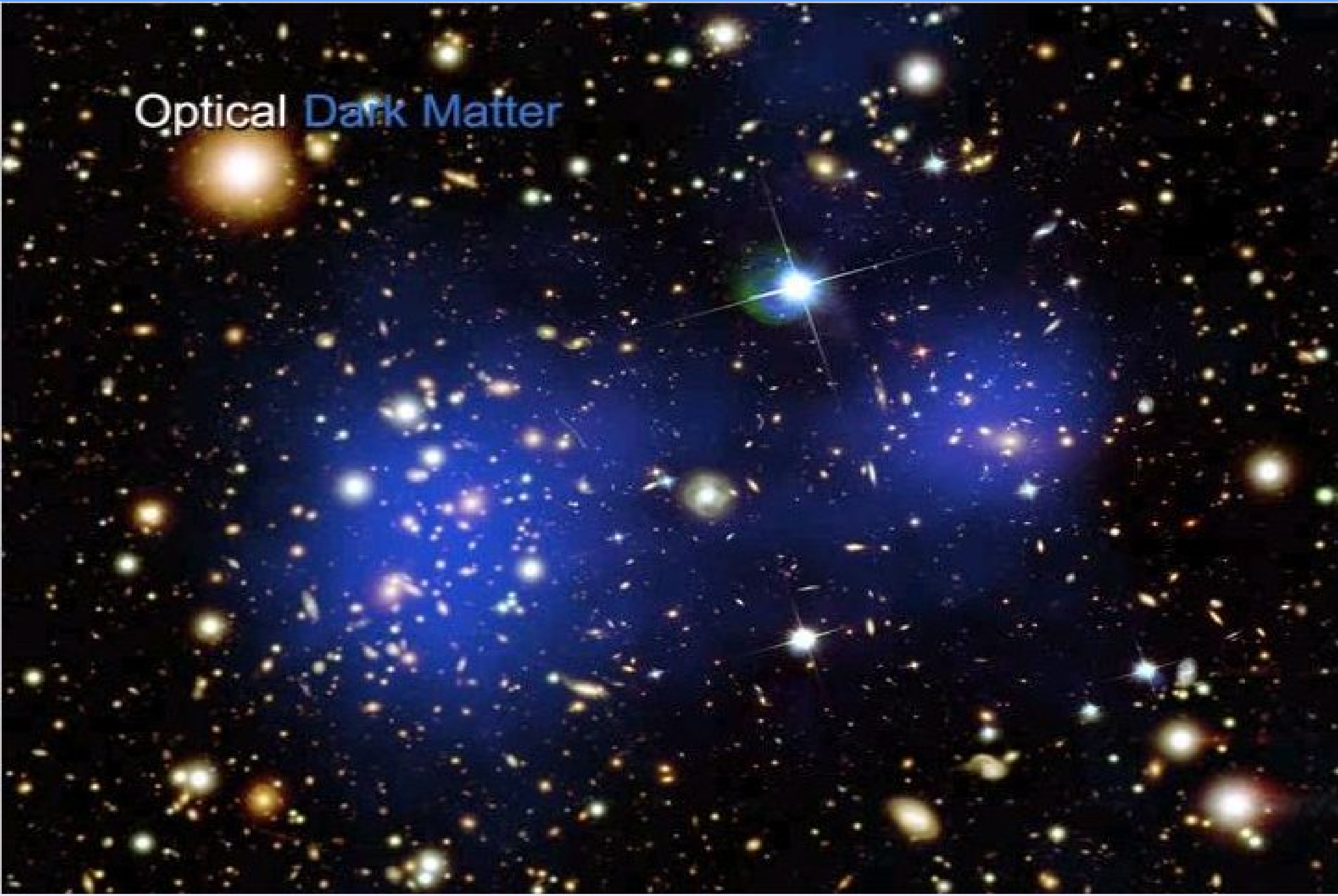
- Interaction of galaxy clusters (Clowe et al. DM2006)




Optical

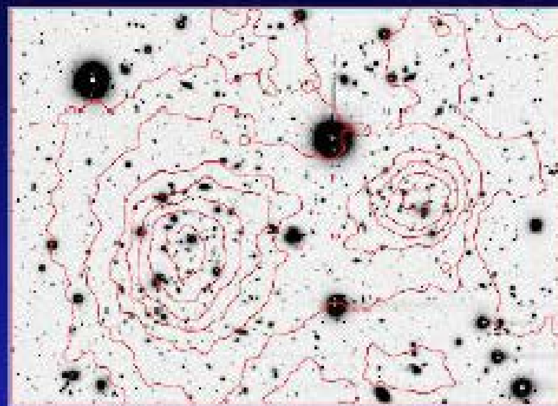

Optical Dark Matter

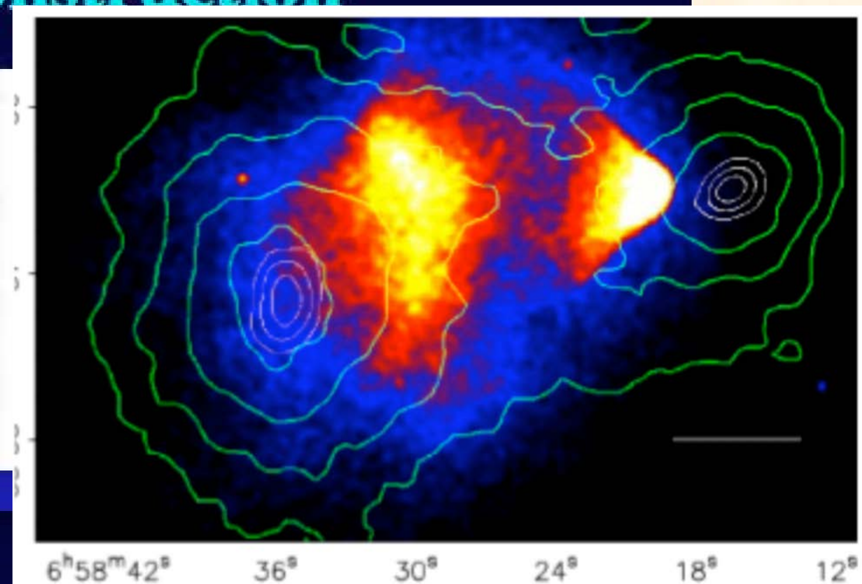

Optical Dark Matter X-ray Gas

# Dark matter wins !

Optical
Dark matter

## Weak lensing reconstruction



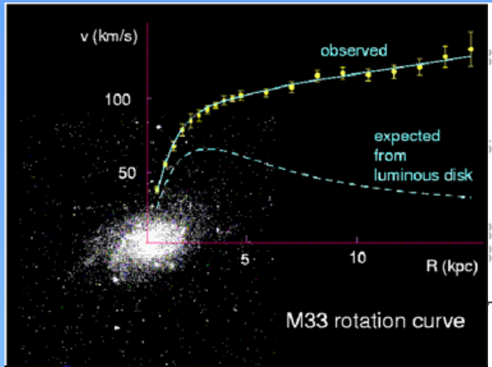


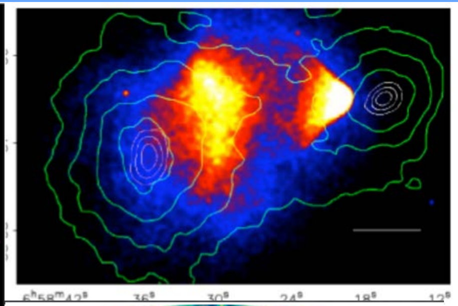

natter

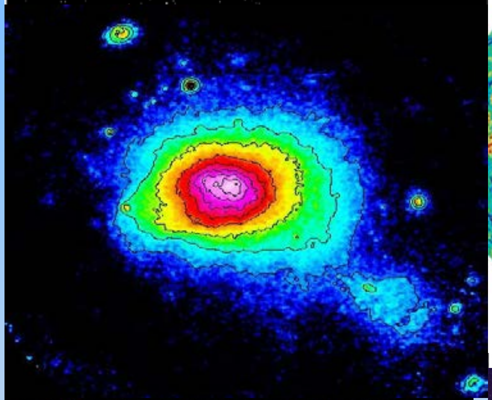
## Conclusions

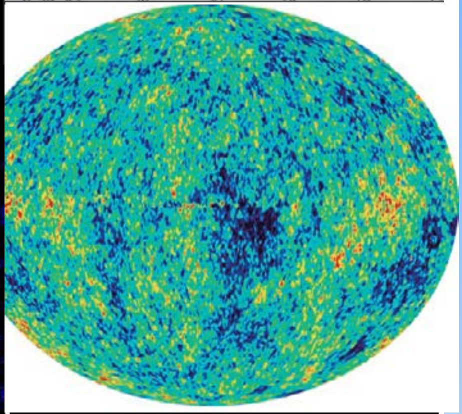
- Weak lensing provides a means to measure the mass of a cluster independent of dynamical state.
- Studies of interacting clusters provide direct proof that dark matter exists independent of any assumptions about gravity or cosmology.
- The survival of the subclump in the 1E0657-556 merger gives an upper limit of $3(0.8)\mathrm{cm}^2\mathrm{g}^{-1}$ for SIDM.

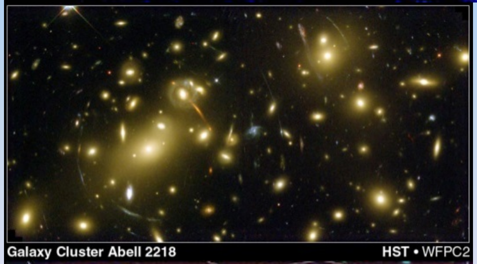
# Standard cosmology

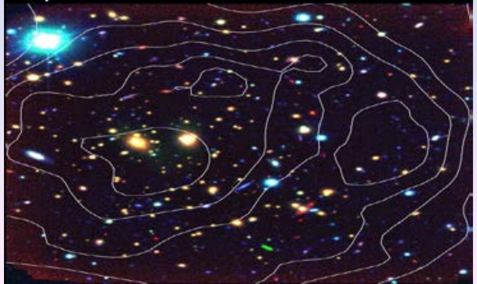


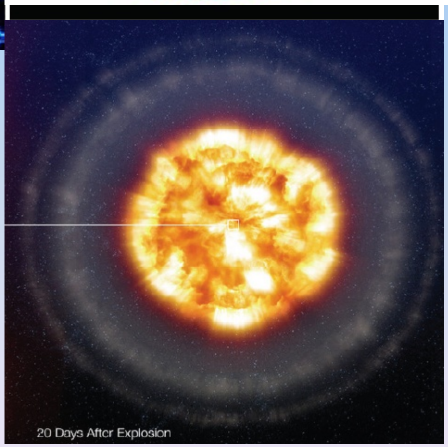



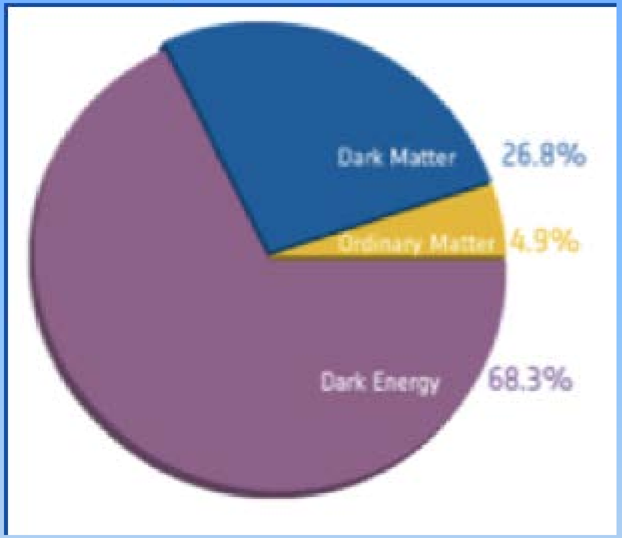






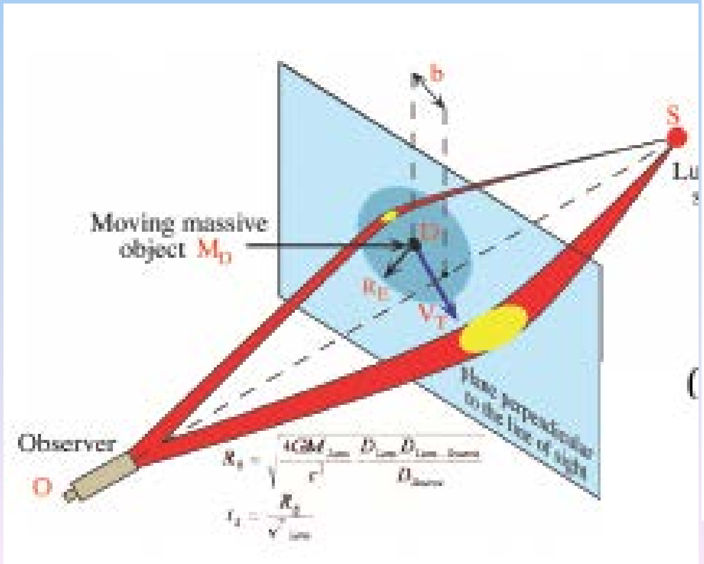



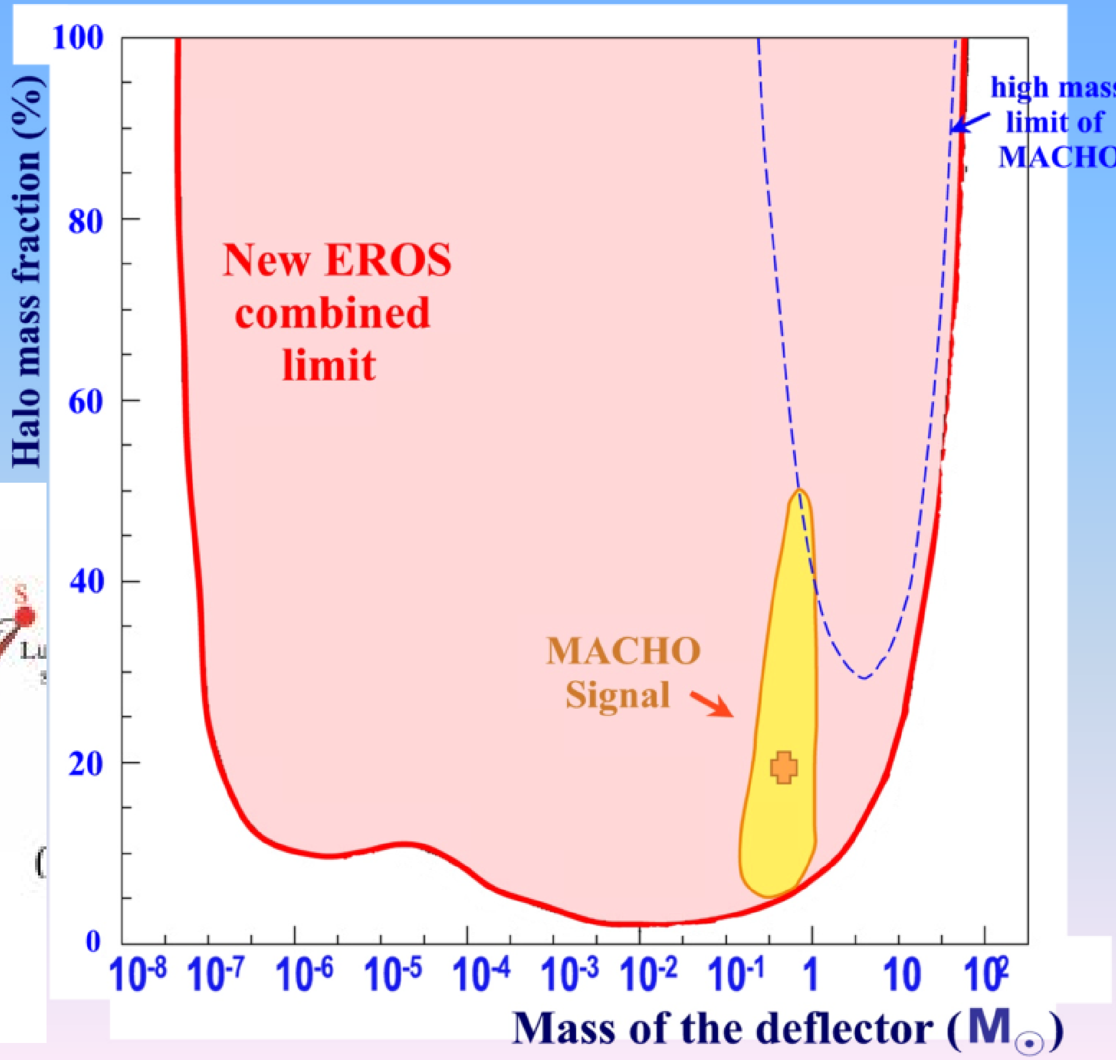


# Nature of dark matter – non-baryonic cold dark matter

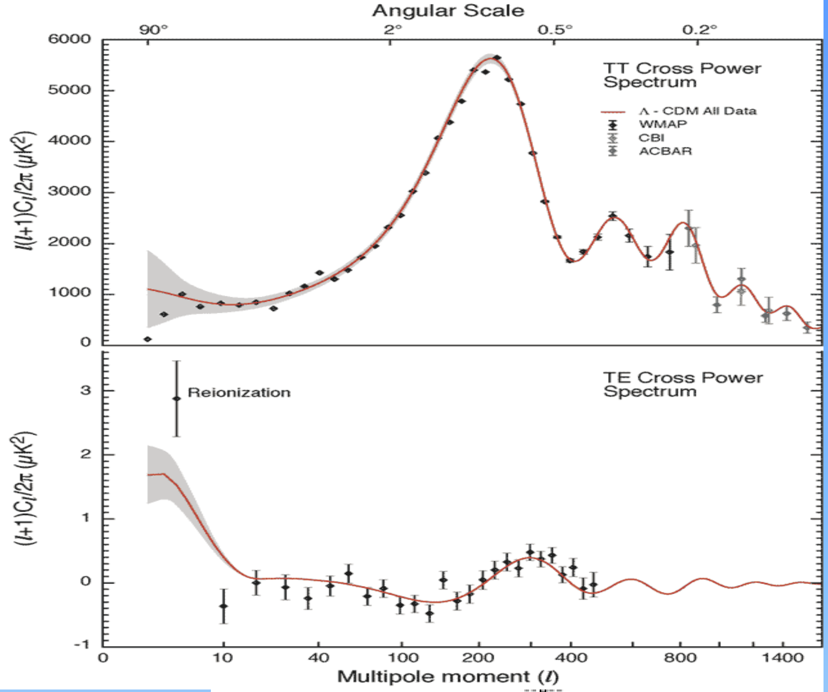
Not in compact form, such as black holes, neutron stars? (MACHO -MAssive Compact Halo Objects)

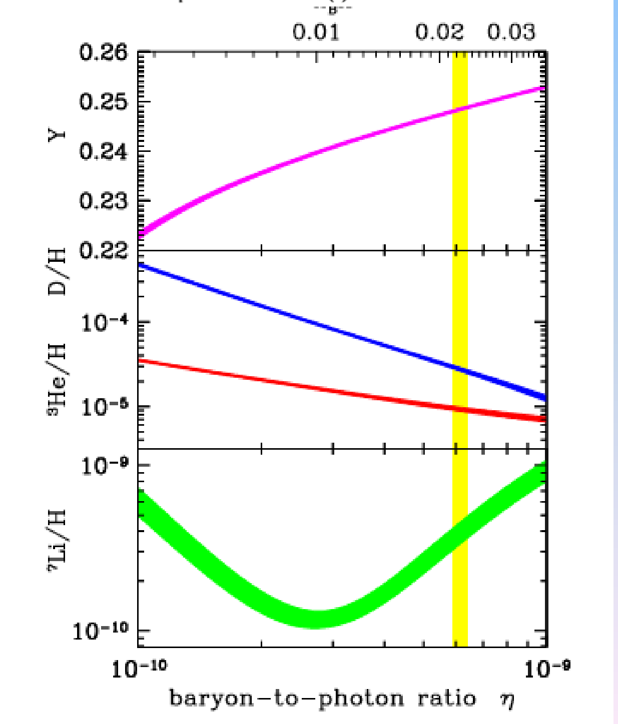


# Non-baryonic

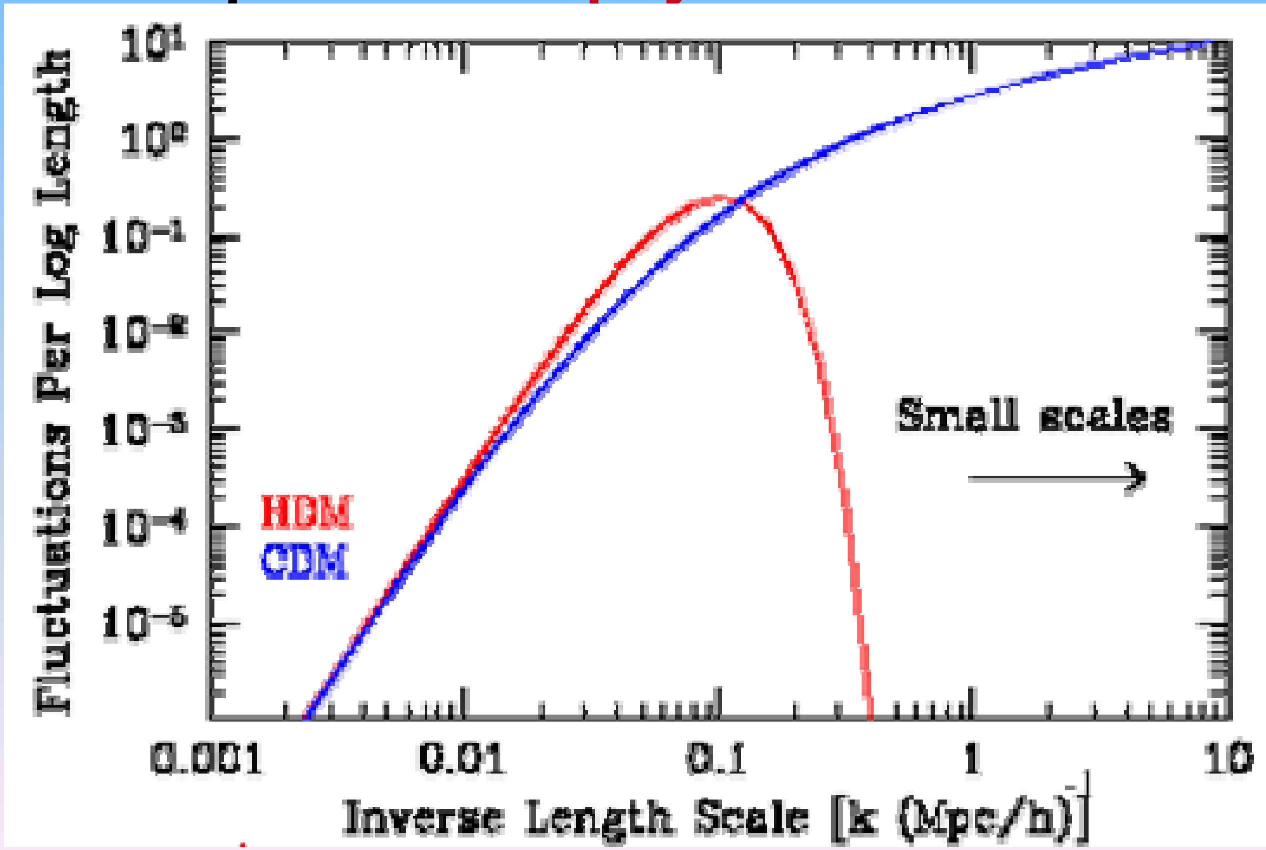
From BBN and CMB, it has $\Omega_B h^2=0.02$+-0.002. Therefore, most dark matter should be non-baryonic. $\Omega_{DM} h^2=0.113$+-0.009



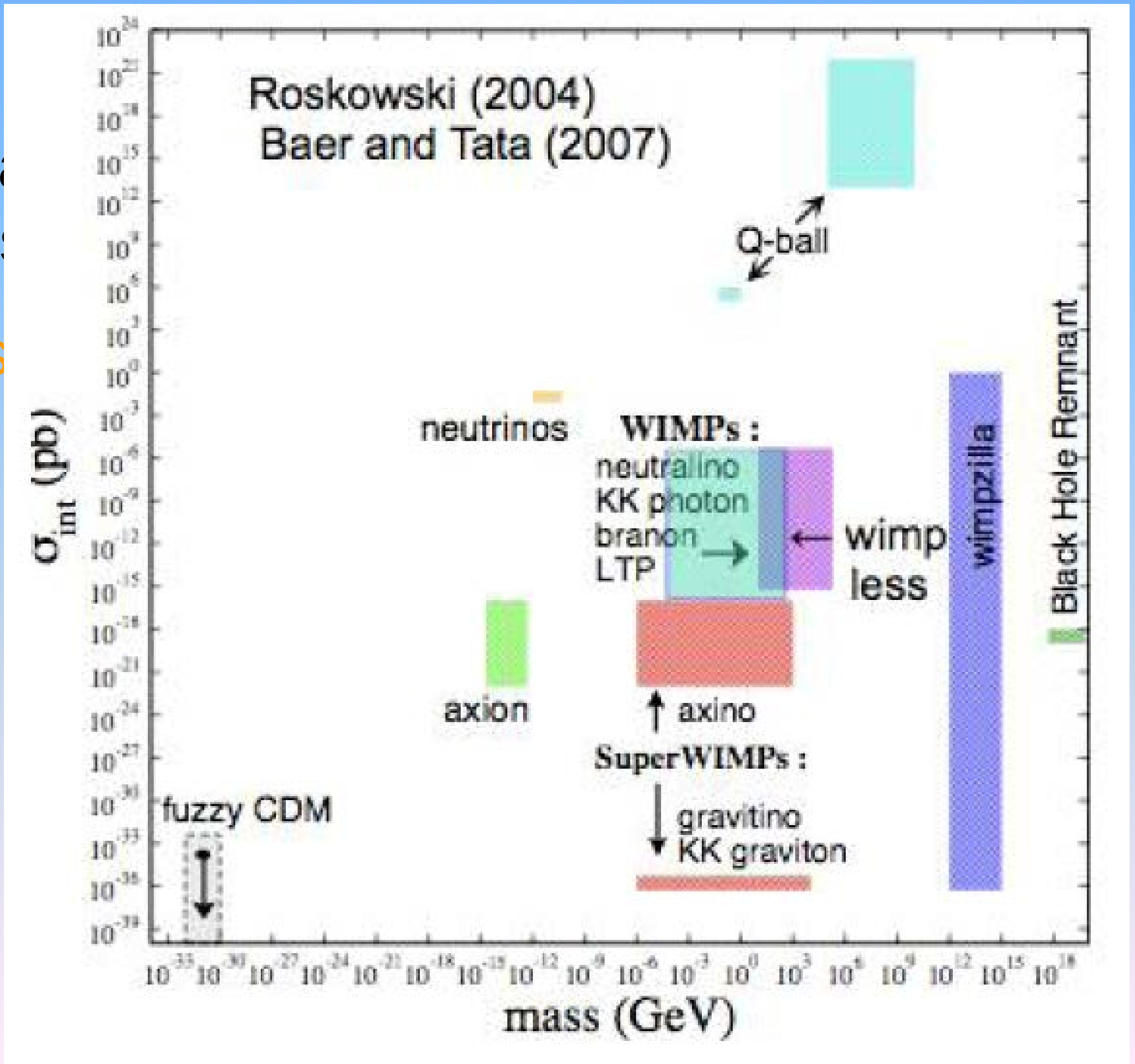
# New physics beyond the SM

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



# Candidates of the cold dark matter－stable、neutral、weak interacting

- There are dozens of theoretical models in the literature
- Weakly Interacting
relics of Big Bang is
independently propo
- such as neutralinos




**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)**

# Thermal production of dark matter

- Assuming a new, stable particle $\chi$ , its mass $M_\chi$ and weak interaction with the SM particles.
- At the early Universe of temperature T, $\chi$ is at thermal equilibrium through $\chi\bar{\chi} \rightarrow l\bar{l}$, for $T >> M_\chi$ the number density is $n_\chi \propto T^3$ , while for $T << M_\chi$ the number density is $n_\chi \propto (mT)^{3/2} e^{-m/T}$
- As the cooling of the Universe, when the reaction rate equates to expanding rate $\Gamma = n_\chi \langle \sigma v \rangle \approx H$ , the particle decouples from the thermal equilibrium. Dark matter as thermal relics freeze in. the comoving number density is then a contant. Introducing $Y = \left( \frac{n_\chi}{s} \right)_{T_f} = \left( \frac{n_\chi}{s} \right)_{T_0}$ , with s the entropy density。

# Hot dark matter

- At decoupling, if $\chi$ is relativistic, both number density of $\chi$ and s are $\propto T^3$, the ratio is independent of temperature, therefore $\rho_\chi{}^0 = M_\chi n_\chi{}^0 = M_\chi s^0 Y(T_f) = \text{const} \cdot M_\chi$. The relic density of hot dark matter is porp to its mass. $\Omega h^2 = \frac{\rho_\chi}{\rho_{\text{tot}}} h^2 = \frac{M\chi}{94.4eV}$ the mass is therefore constrained by cosmology.
- Neutrino is hot dark matter, its abundance and it mass are constrained by SDSS and Planck
- $\Omega_\nu h^2 < 0.05\Omega_{\text{CDM}} h^2 \Leftrightarrow \sum_i m_{\nu_i} < 0.6eV$ (Planck 2013)

# Cold dark matter

- The CDM is non-relativistic at decoupling, its number density $n_\chi$ is exponentially suppressed, therefore the ratio to S depends strongly on its decoupling temperature, $n_\chi(T_f) \approx H(T_f)/\langle \sigma v \rangle_{T_f}$ applying the relations

$$H = 1.66 g_*^{1/2} T^2 / M_{pl} \qquad s \cong 0.4 g_* T^3 \qquad \Gamma \sim H \rightarrow T_f \approx M_\chi / 20$$

we get

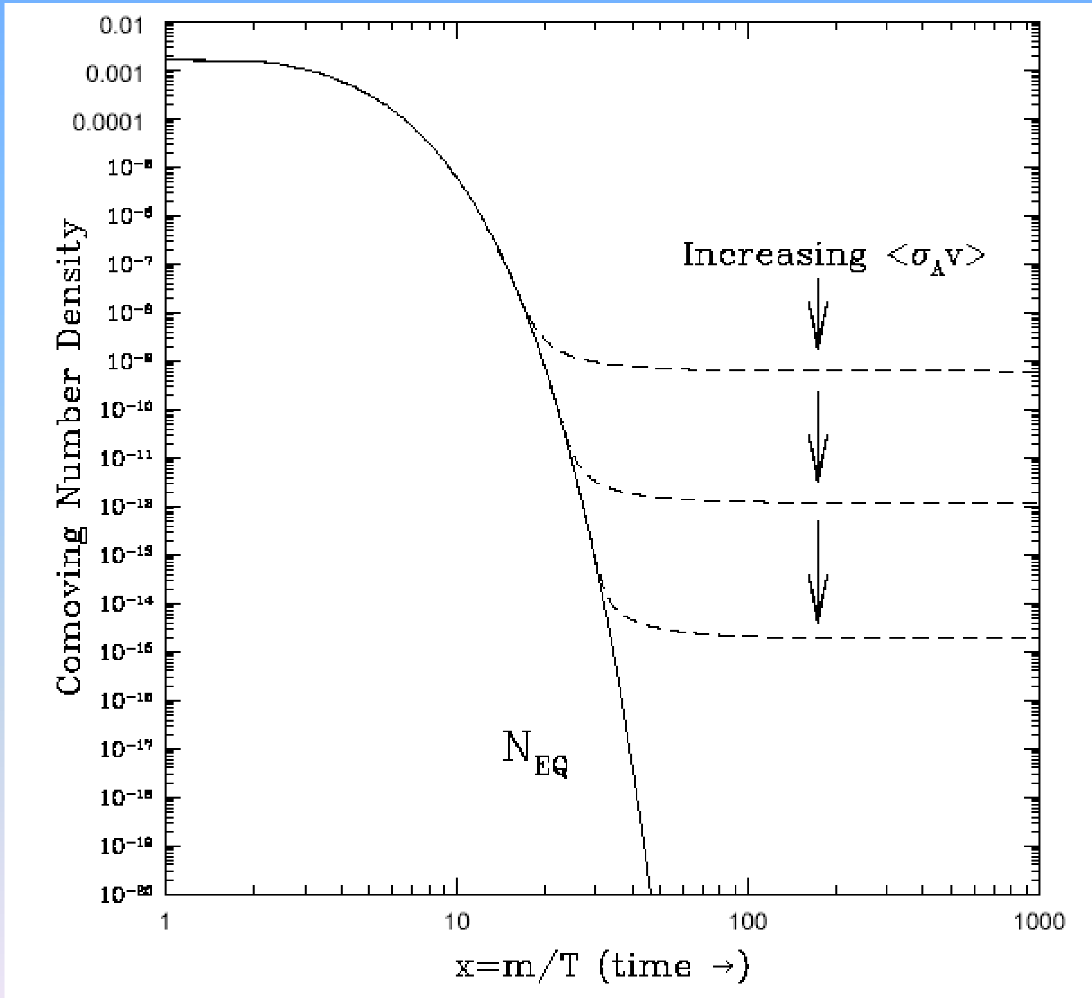
$$\Omega_\chi h^2 = \frac{n_\chi^0 M_\chi}{\rho_{\text{tot}}} h^2 = \frac{s^0 Y(T_f) M_\chi}{\rho_{\text{tot}}} h^2 \approx \frac{3 \cdot 10^{-27} cm^{-3} s^{-1}}{\langle \sigma v \rangle_{T_f}}$$

- Here $\langle \sigma v \rangle$ determines the strength of the interaction.

# Density via interaction strength

We have to solve the Boltzmann equation numerically, taking into account the threshold and co-annihilation $\Delta m < T$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_A v \rangle \left[ (n_\chi)^2 - \left( n_\chi^{eq} \right)^2 \right]$$



# Why WIMP (Weak interacting massive particles)

- From $\Omega_\chi h^2 \approx \frac{3\cdot 10^{-27} cm^3 s^{-1}}{\langle \sigma v \rangle_{T_f}}$, we have

$$\sigma \sim \frac{\alpha^2}{M_{\text{weak}}^2} \sim 10^{-25} cm^3 s^{-1}$$ for $\alpha \sim 10^{-2}$ $M_{\text{weak}} \sim 100 GeV$

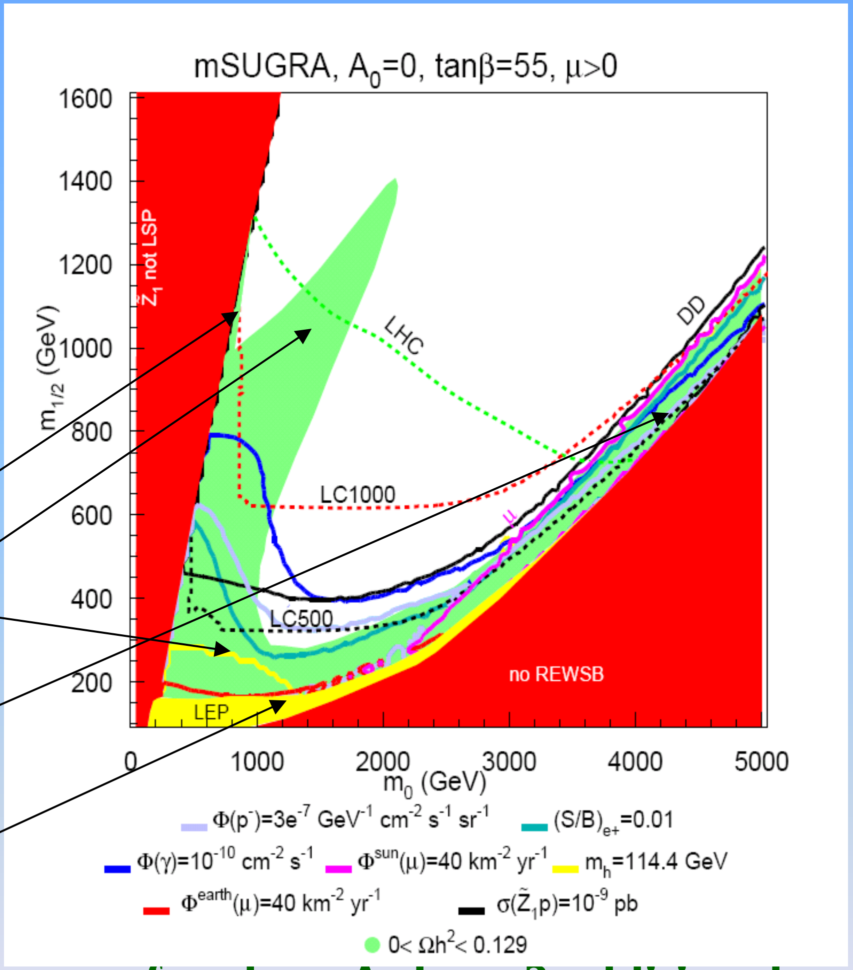
$$v^2 \approx c^2 / 20 \qquad \langle \sigma v \rangle \sim 10^{-26} cm^3 s^{-1}$$

**Therefore, WIMP is the most nature dark matter candidate if we take DM as thermal relics of the big bang.**

Conversely, precise cosmological measurements of the dark matter abundance constrain the particle physics model strongly.

## mSUGRA or CMSSM: simplest (and most constrained) model for supersymmetric dark matter

H. Baer, A. Belyaev, T. Krupovnickas, J. O'Farrill, JCAP 0408:005,2004




**R-parity conservation, radiative electroweak symmetry breaking**

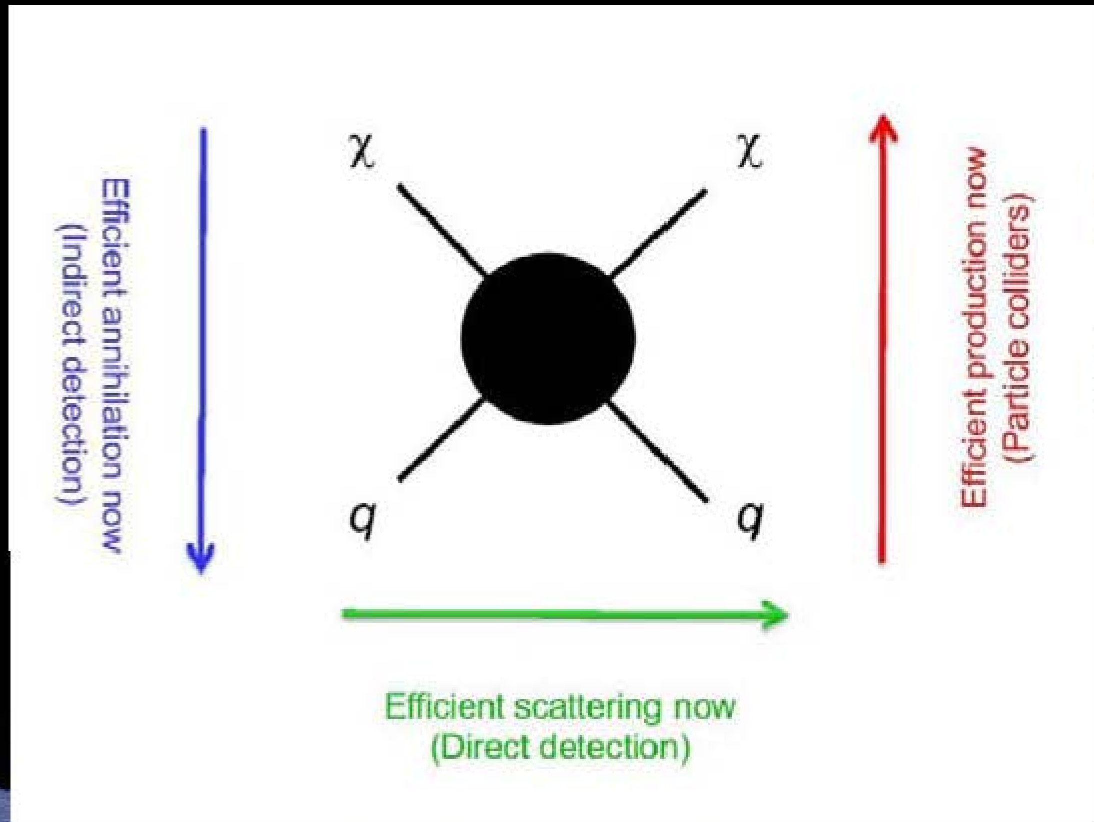
**Free parameters (set at GUT scale): $m_0$, $m_{1/2}$, tan β, $A_0$, sign(μ)**

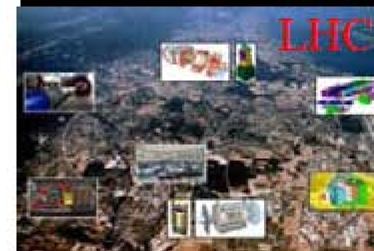
**4 main regions where neutralino fulfills WMAP relic density:**

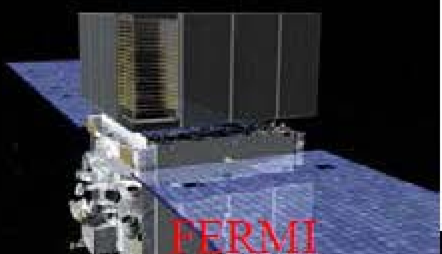
- **bulk region (low $m_0$ and $m_{1/2}$)**
- **stau coannihilation region $m_\chi \approx m_{stau}$**
- **hyperbolic branch/focus point ($m_0 >> m_{1/2}$)**
- **funnel region ($m_{A,H} \approx 2m_\chi$)**
- **(5th region? h pole region, large $m_t$ ?)**

**However, general MSSM model versions give more freedom. At least 3 additional parameters: μ, $A_t$, $A_b$ (and perhaps several more…)**

# Different approaches to search for Dark Matter

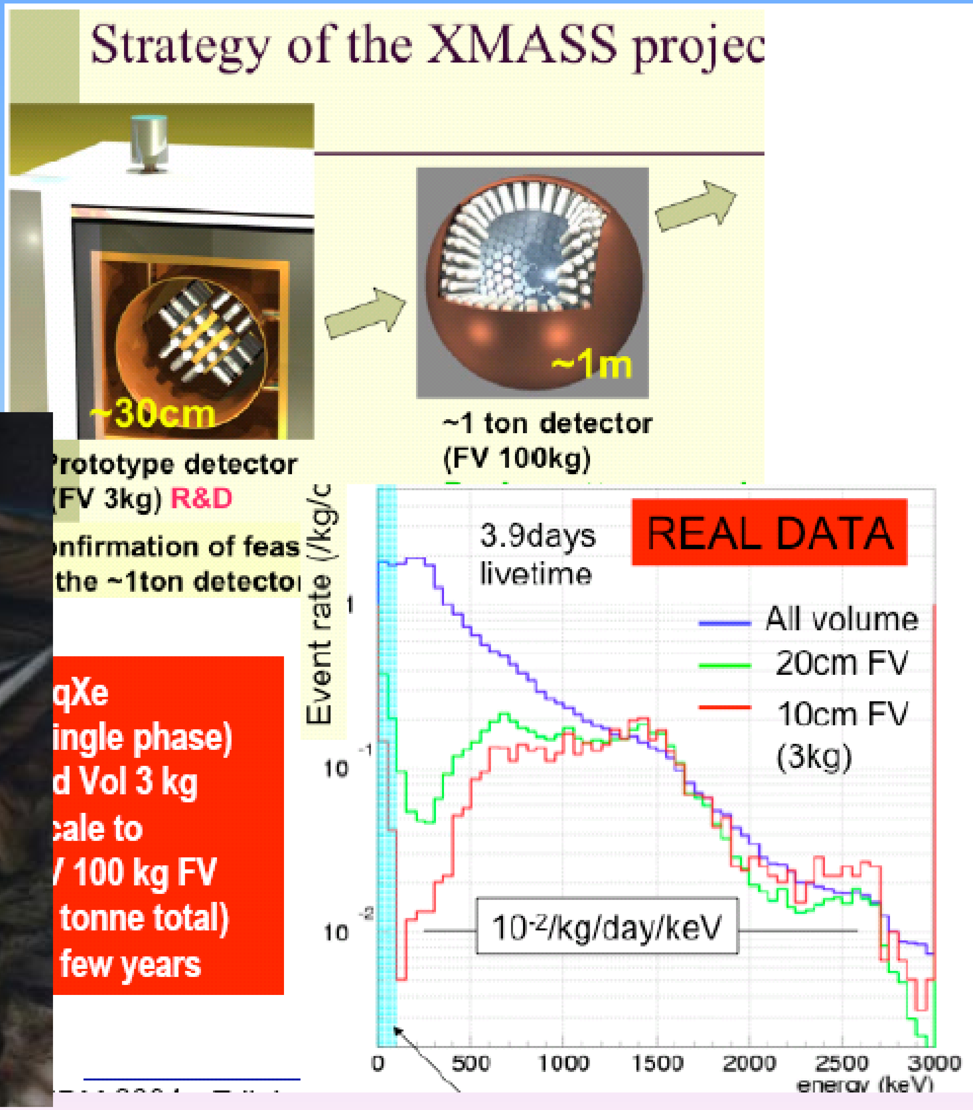


*Adapted from P. Lipari*

# 直接探测

(暗物质像空气一样充满整个银河系)

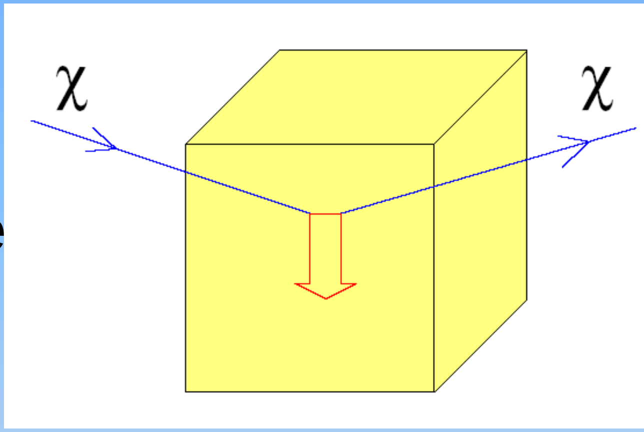
探测暗物质粒子与探测器碰撞所产生的信号



# Direct detection of WIMP

- Detect the signal when a WIMP collides with the nuclei. The interaction is related with annihilation via a cross symmetry.

$$\chi\bar{\chi} \to l\bar{l} \Leftrightarrow \chi l \to \chi l$$



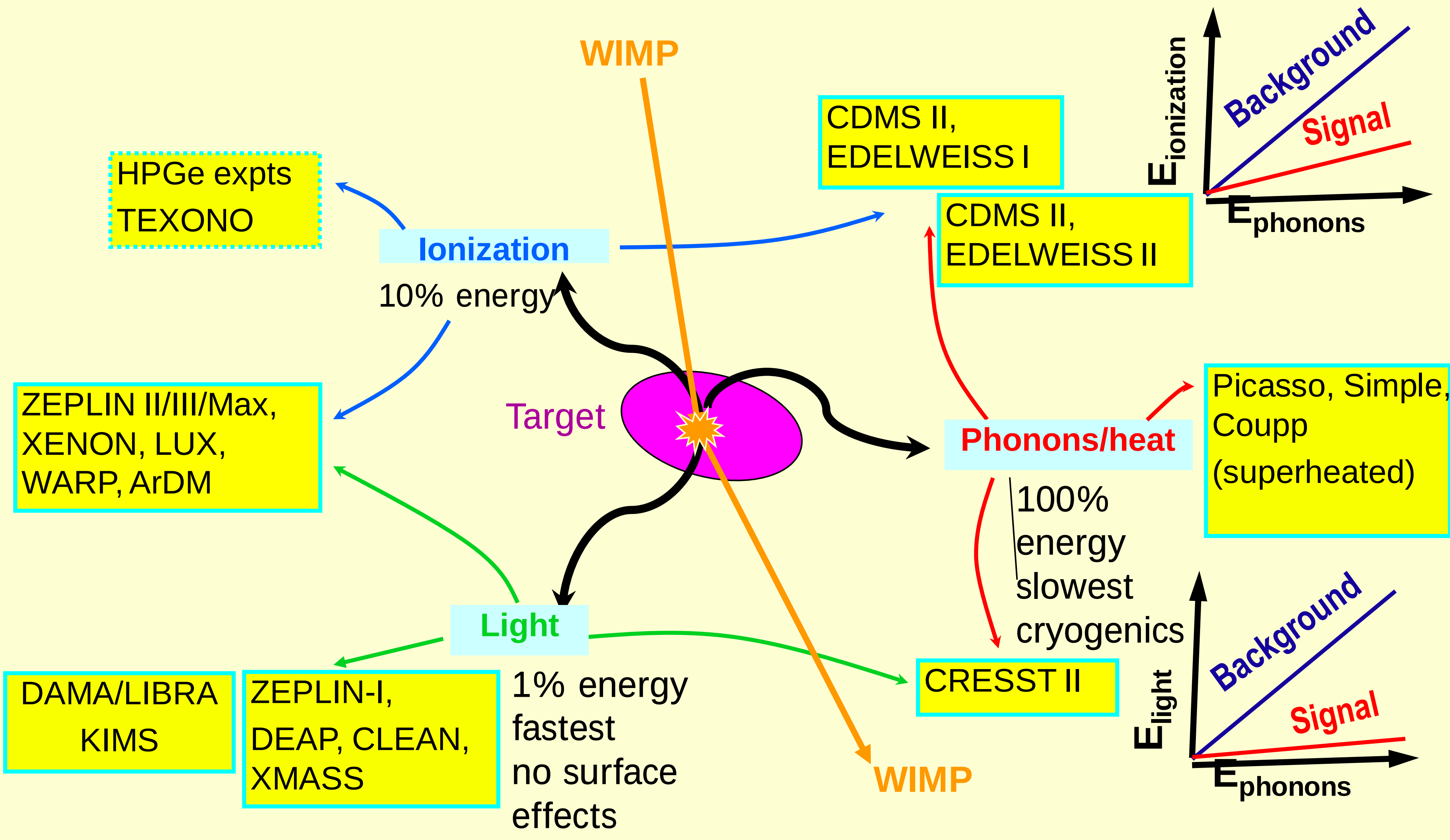

Therefore we expect small but non-zero interaction between the WIMP and nucle

- The scattering includes elastic and inelastic. The inelastic process is extremely weak and radiation from excited nuclei is hard to distinguish from the background. At present the experiments measure the elastic scattering.
- The energy deposited in the detector is measured. For typical $M_\chi$ and velocity of the WIMP, the energy is at the order of KeV.

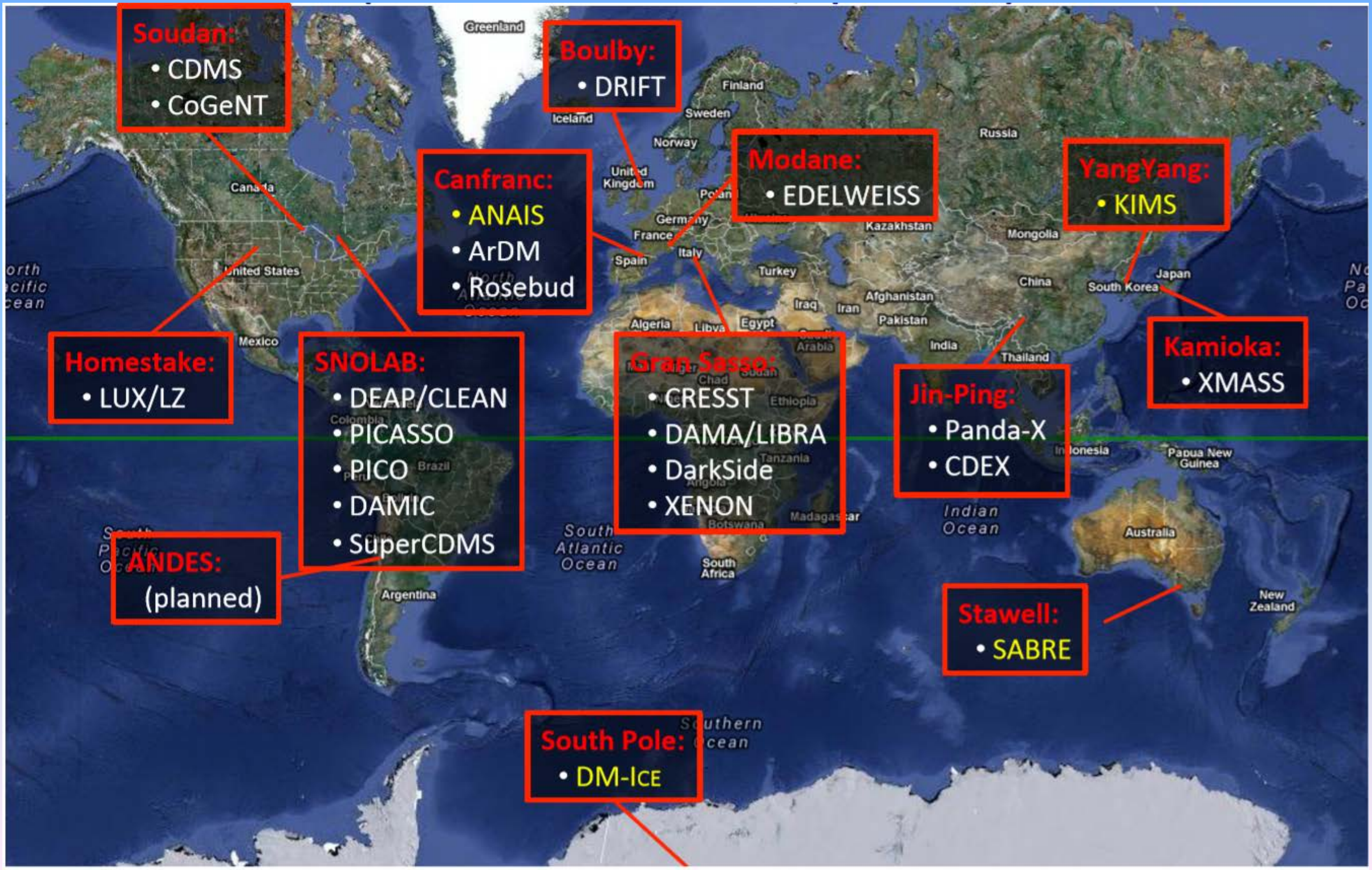
# Elastic scattering

- The effective coupling between $\chi$ and quark can be divided to the scalar, pseudo-scalar, vector, axial-vector and tensor types. For the extreme non-relativistic Majorana neutralino, the interaction is simplified to two cases: spin-dependent and spin-independent coupling.
- For the SD coupling WIMP couples to the spin of the nucleus; while the SI coupling WIMP couples to the mass of the nucleus.

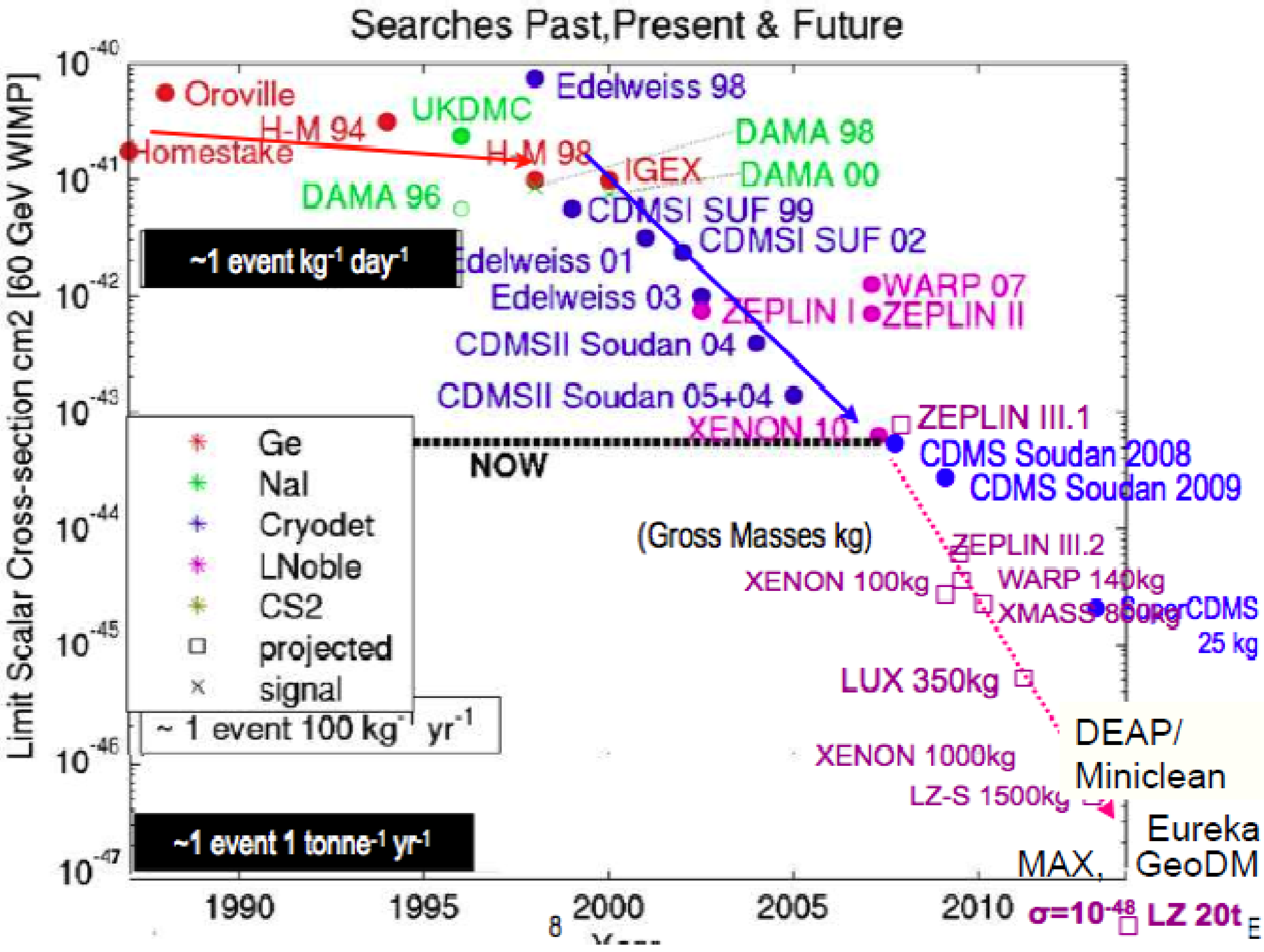
# Detector Techniques - Present Focus : Nuclear Vs Electron recoils



# Underground labs and experiments



# DM Direct Search Progress Over Time

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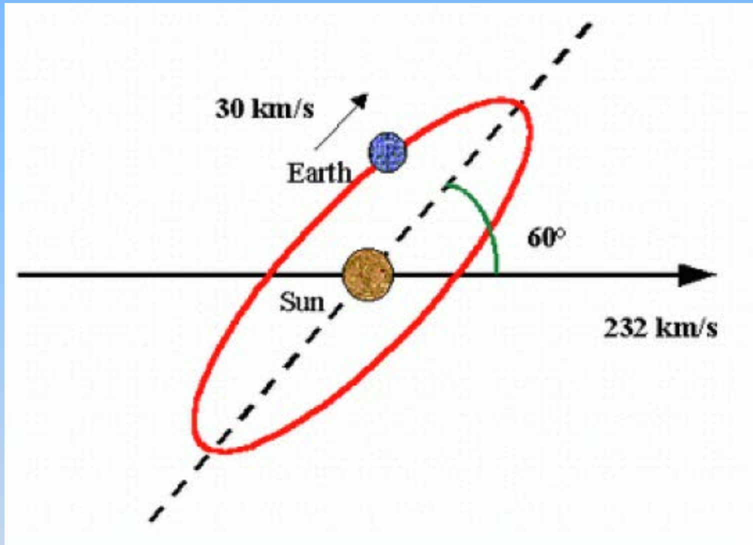
# DAMA confirms the solar modulation signals at 9 **σ**

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

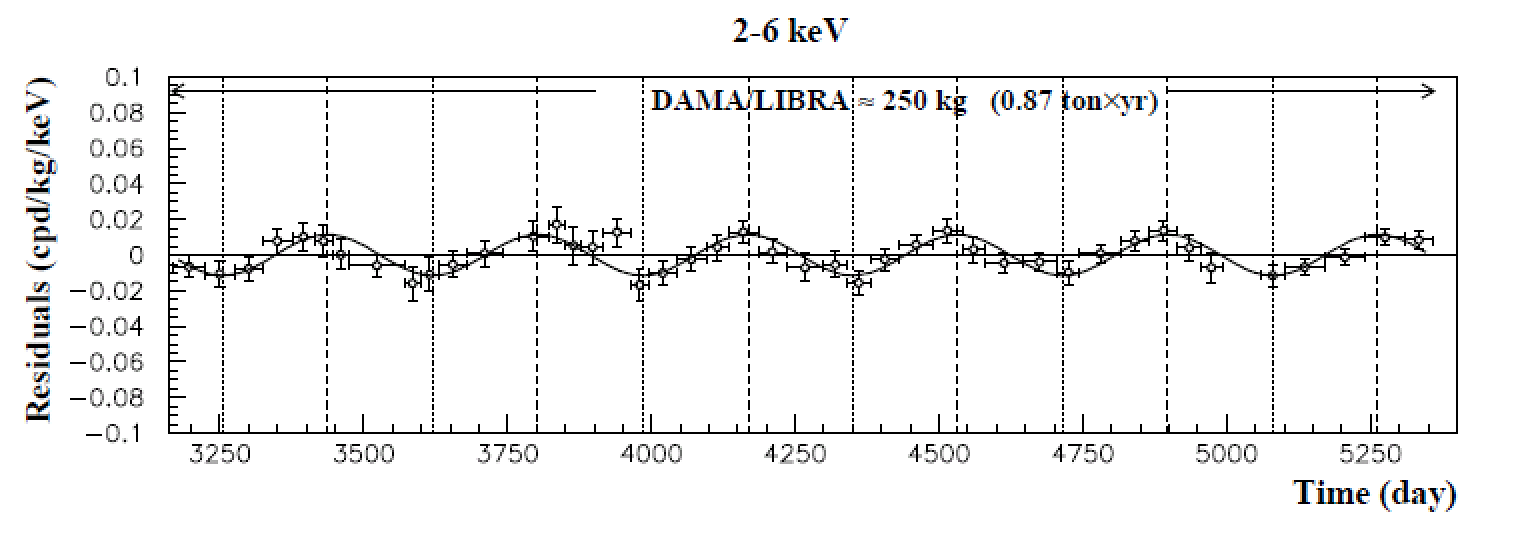
$$v_e = v_\odot + v_{orb} \cos\gamma \cos[\omega(t - t_0)]$$

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



# DAMA观测到9σ的年调制效应

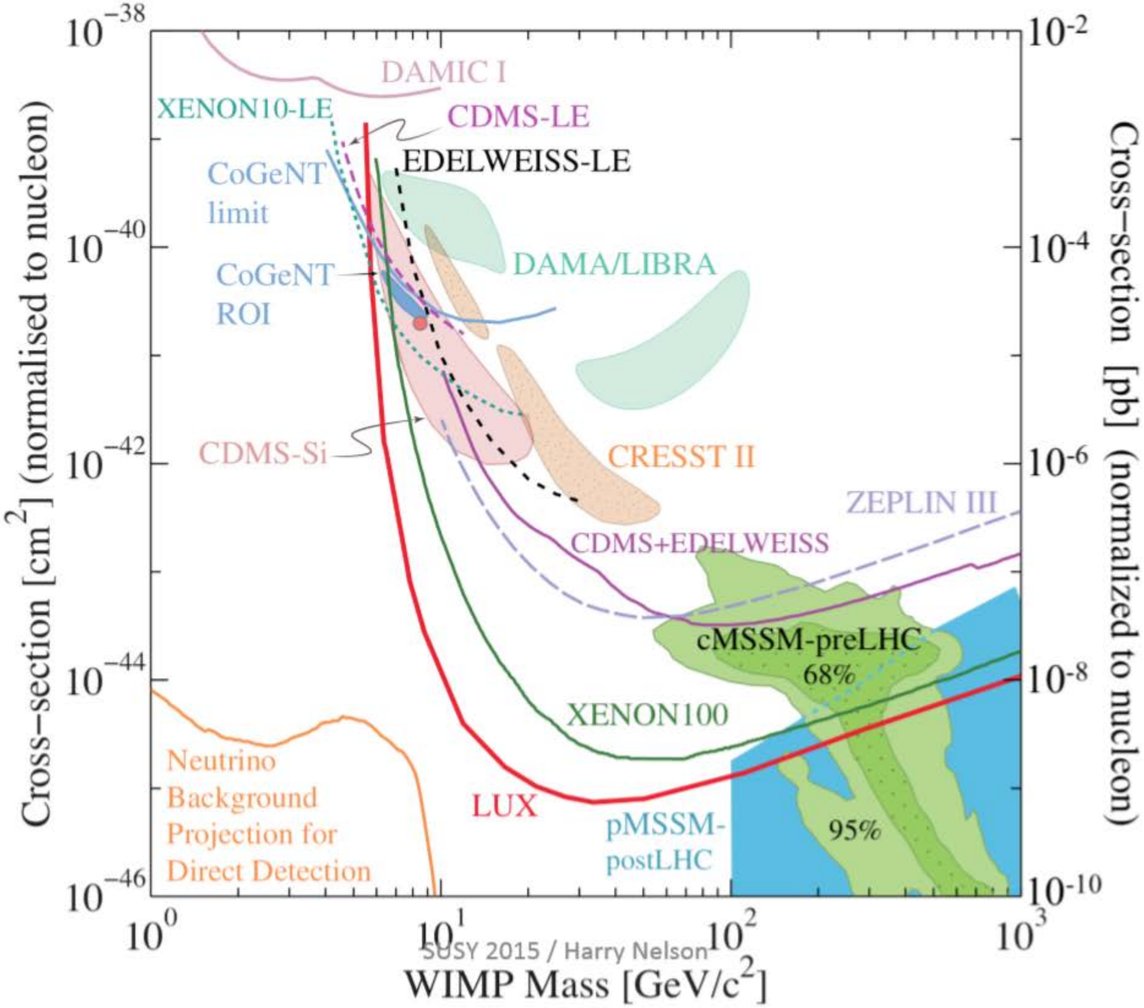
- Total exposure reaches 1.17 ton×yr,13yr



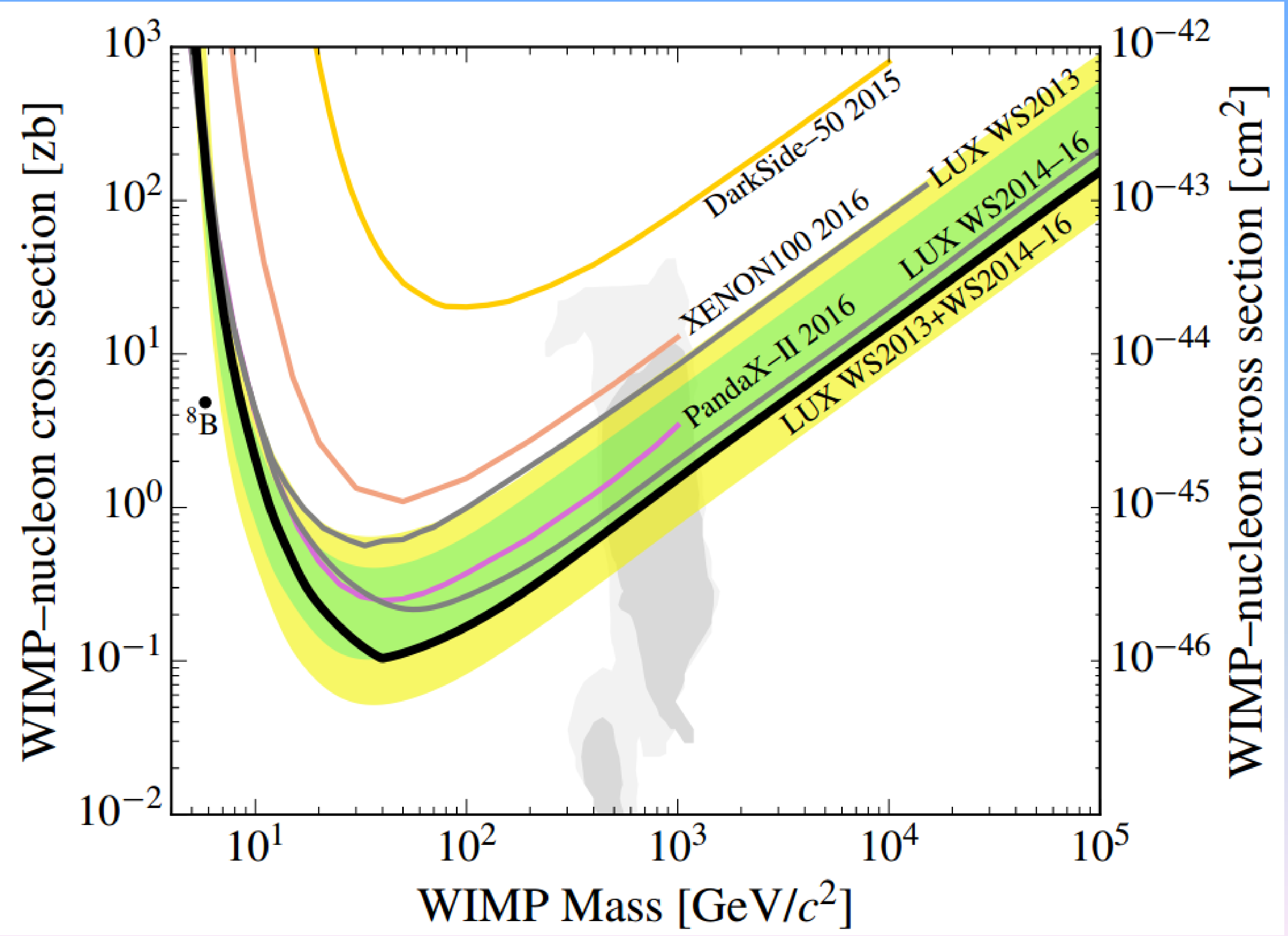

| Energy interval | $A$ (cpd/kg/keV) | $T = \frac{2\pi}{\omega}$ (yr) | $t_0$ (days) | C. L. |
|---|---|---|---|---|
| 2-4 | (0.0194±0.0022) | (0.996±0.002) | 136±7 | $8.8\sigma$ |
| 2-5 | (0.0149±0.0016) | (0.997±0.002) | 142±7 | $9.3\sigma$ |
| 2-6 | (0.0116±0.0013) | (0.999±0.002) | 146±7 | $8.9\sigma$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

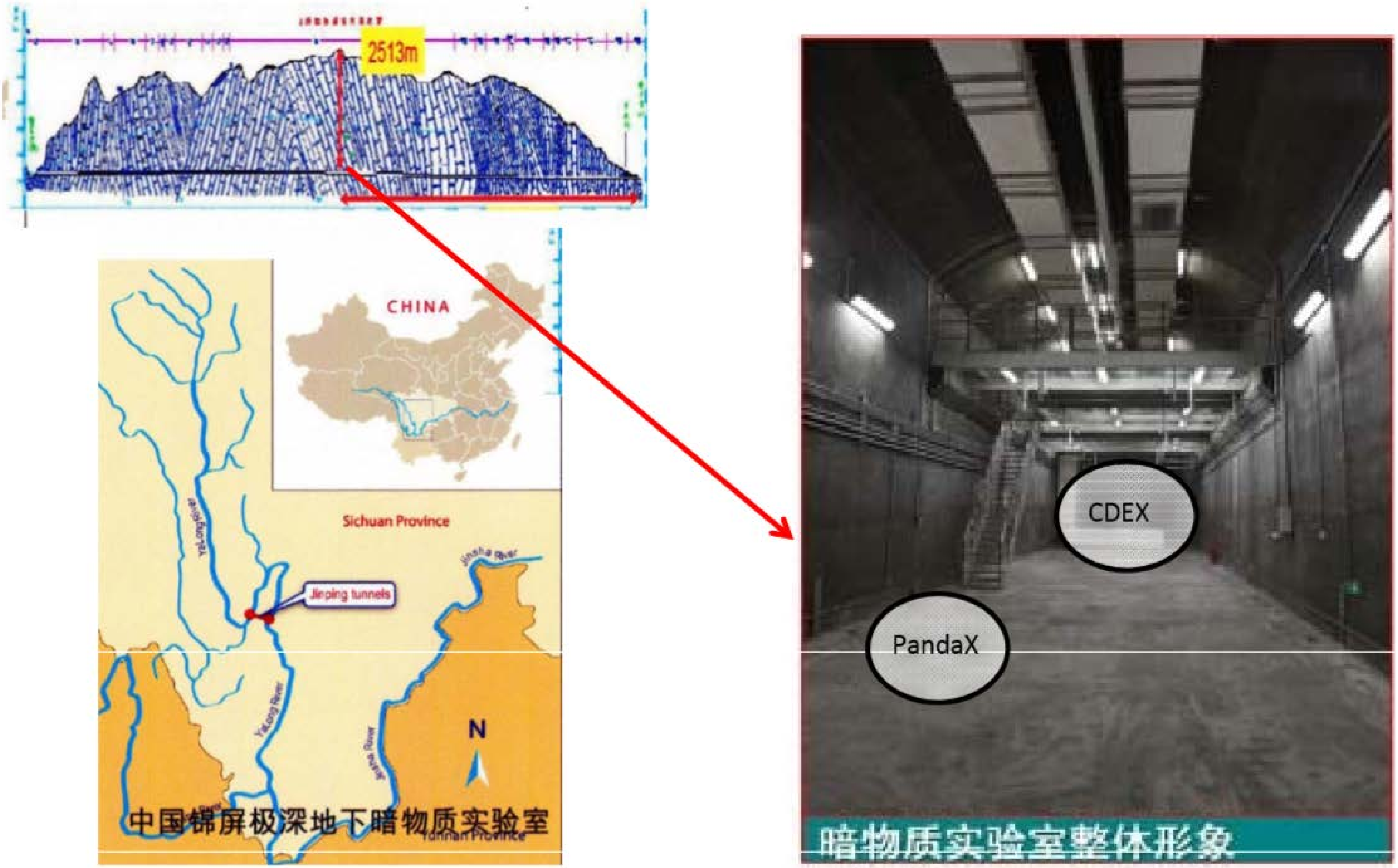
# Summary of the DD results (2015)

**missing: new Darkside-50, CDEX, CRESST-II, PandaX I, PICO, DAMIC**



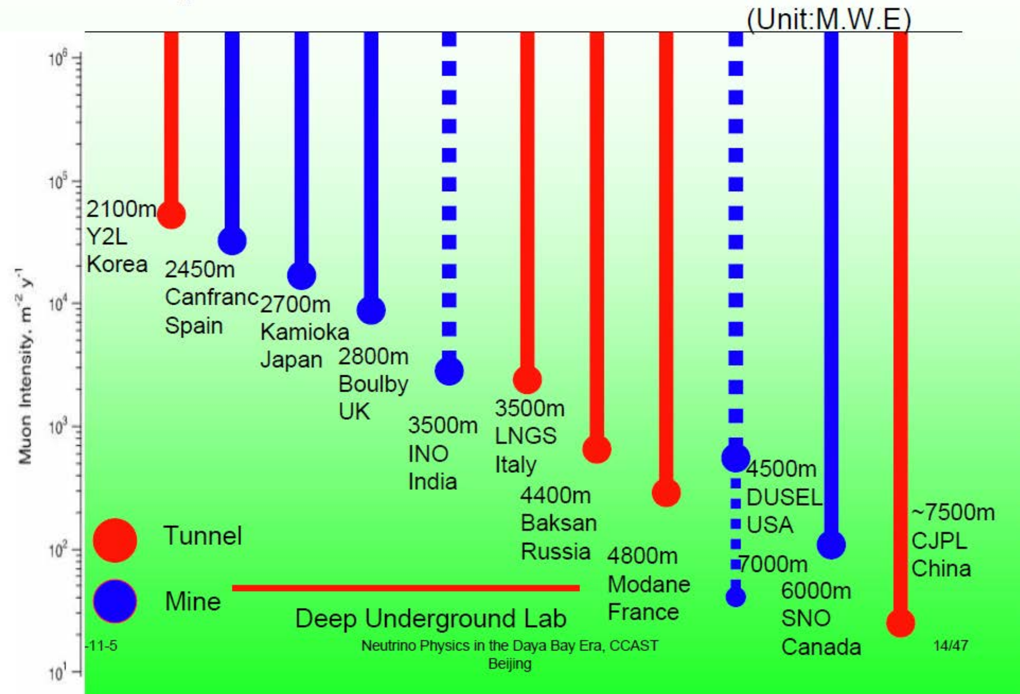
# Latest results 2017





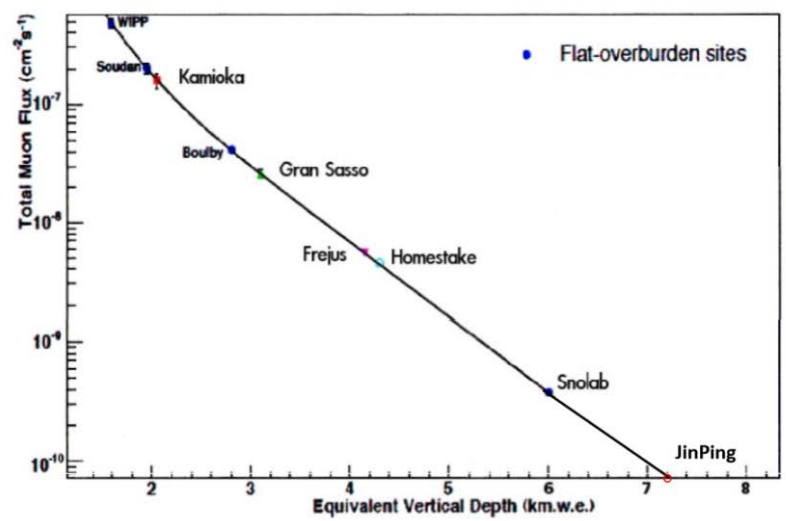

- Deepest lab in operation: 7,200 mwe (66 $\mu/m^2/yr$) → μ veto shield unnecessary
- Radiopure “marble” mountain → water shield not needed
- Middle of 18 km tunnel → easy access by road
- Cavern floor and walls coated with Rn blocking paint
- Scalable design → room to grow

# Comparison of main ULs in the world

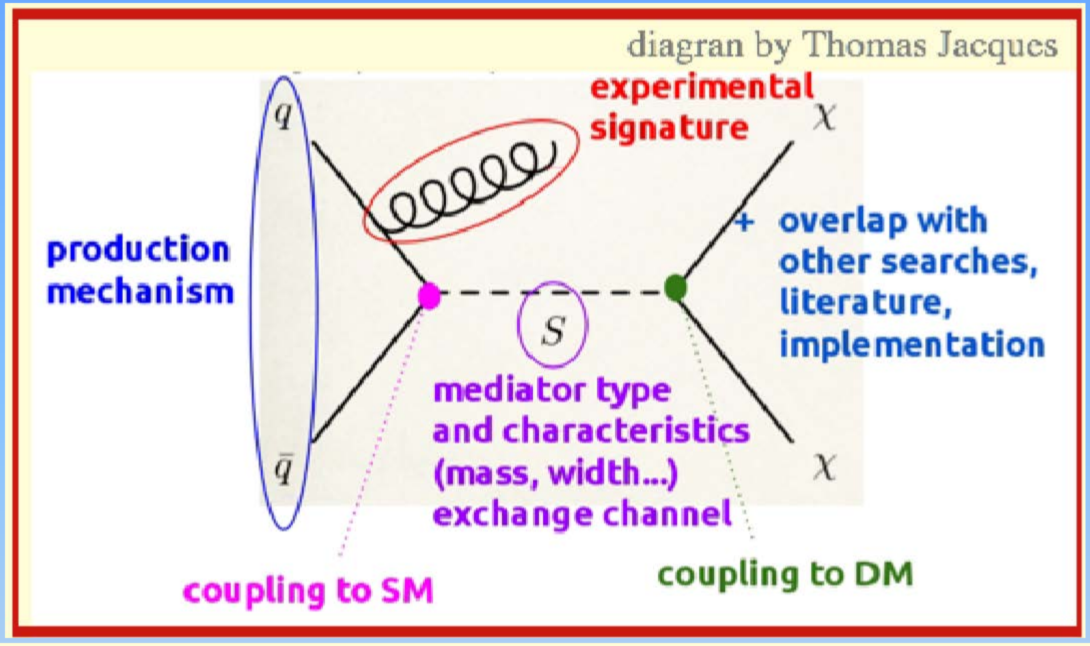



# CJPL: A low Background Facility

low muon flux



# Collider search of DM



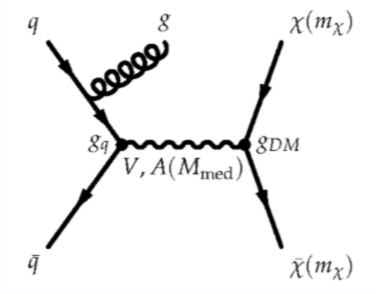

**Signatures:**

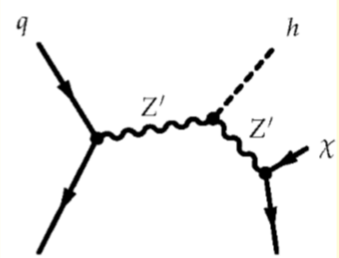
jet + $E_T^{miss}$

EW Boson + $E_T^{miss}$

Higgs + $E_T^{miss}$

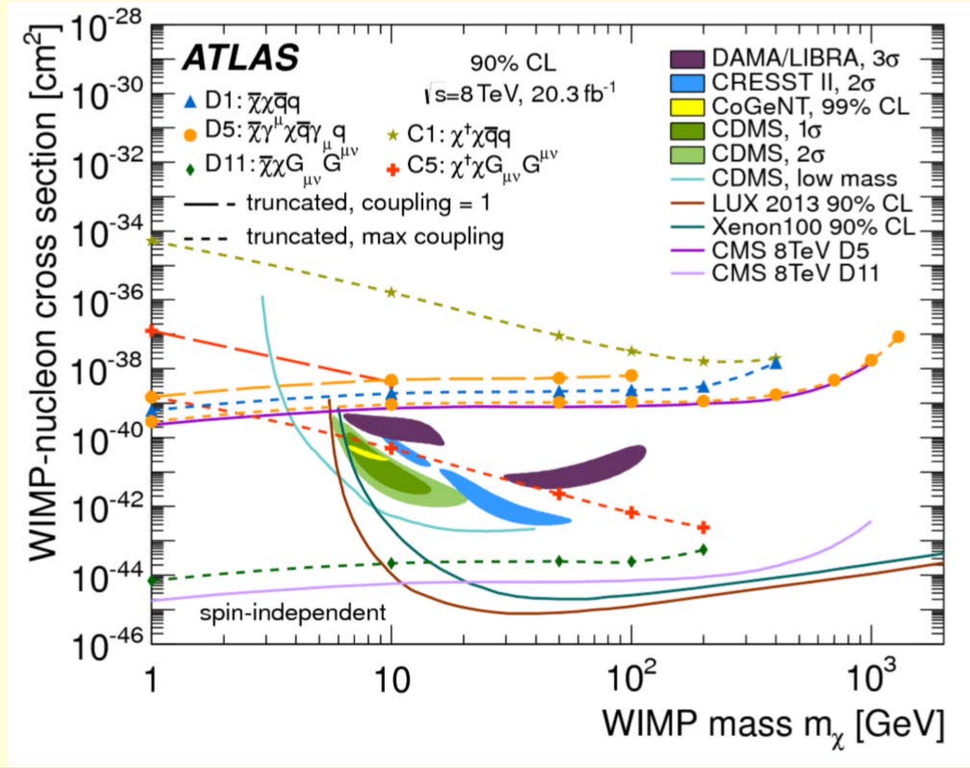
HF + $E_T^{miss}$

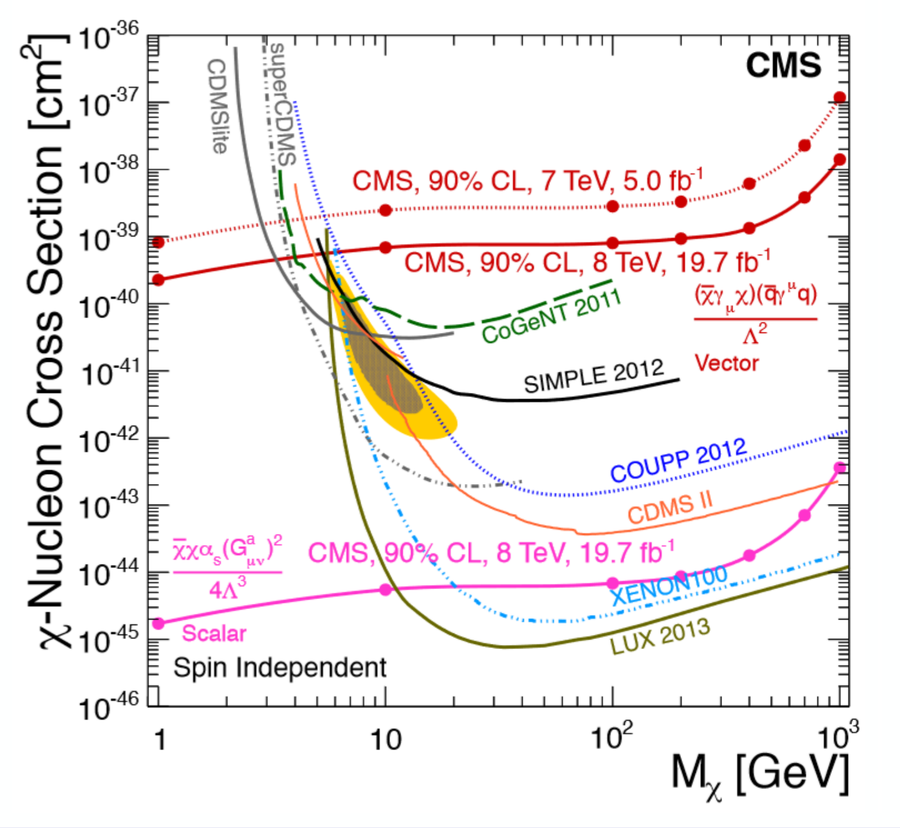




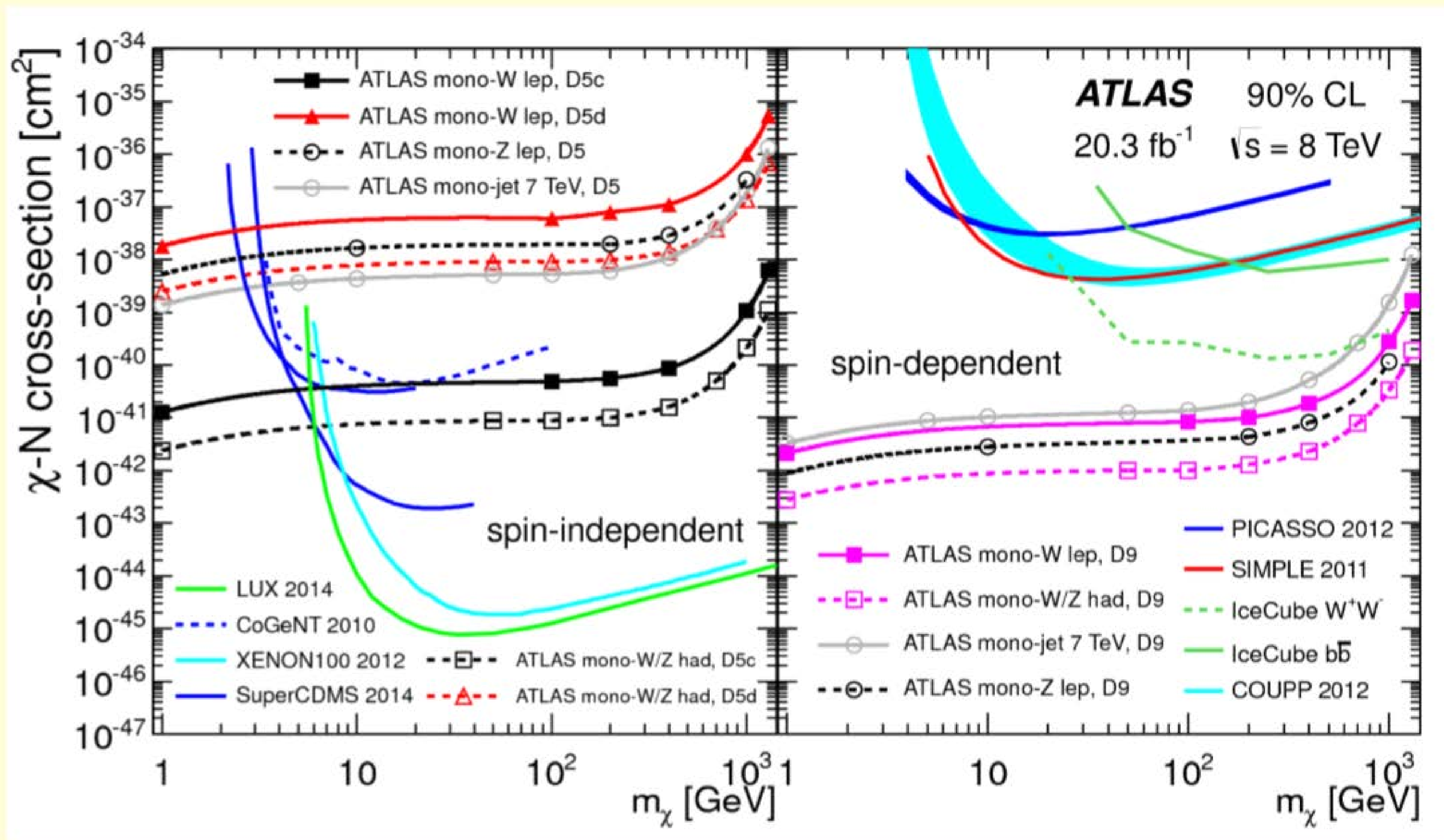
(a)

# Collider vs direct detection

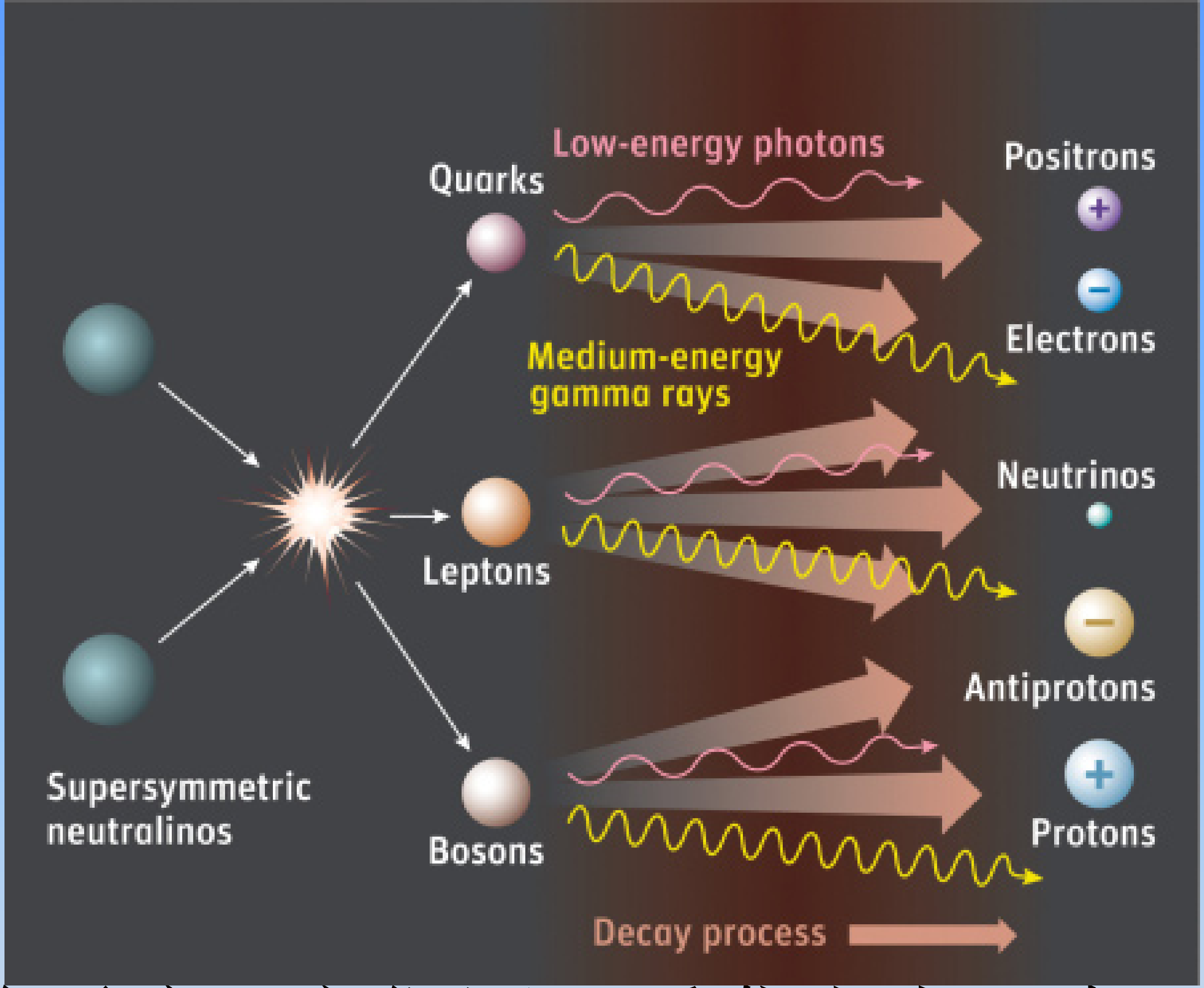


# Spin dependent results



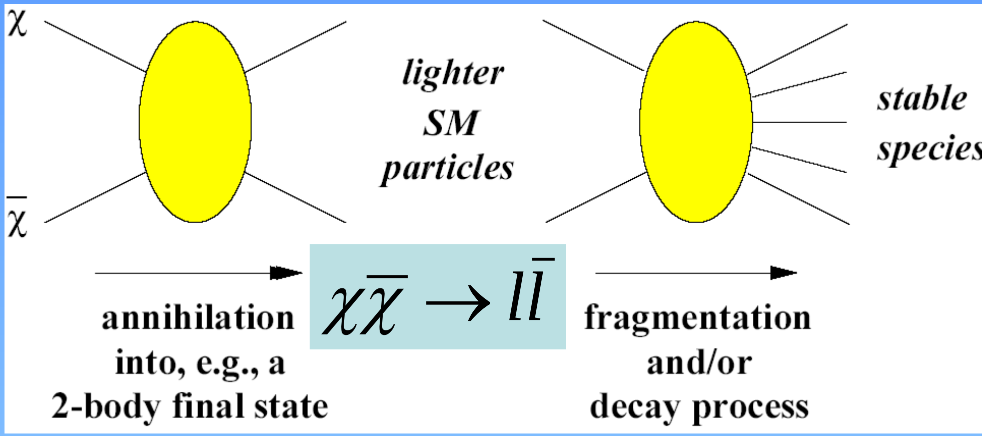
# 间接探测




- 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。

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

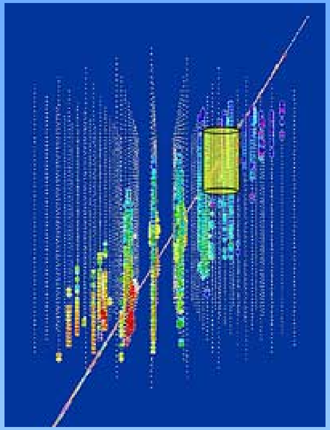
# Indirect detection of WIMP

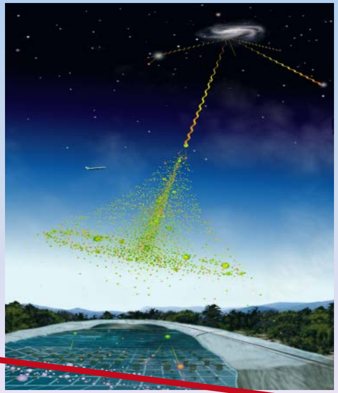



- Indirect detection detects the annihilation products of the dark matter. The annihilation rate is proportional to the square of the dark matter density $\Gamma_{\rm ann} = \frac{\langle \sigma v \rangle n^2}{2} = \frac{\langle \sigma v \rangle \rho^2}{2m_\chi^2}$.
- For the average density of DM in the Universe the annihilation is negligible. However the DM density at somewhere is very high the annihilation rate is also high.
- According to the source the experiments are divided in to: detection of neutrinos from the sun or the earth; cosmic rays from the MW or extra-galaxies; gamma rays in the halo center or from the subhalos.

# What Tools Do We Use?

- **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
- *DAMPE/HERD/LHAASO measure electron spectrum*

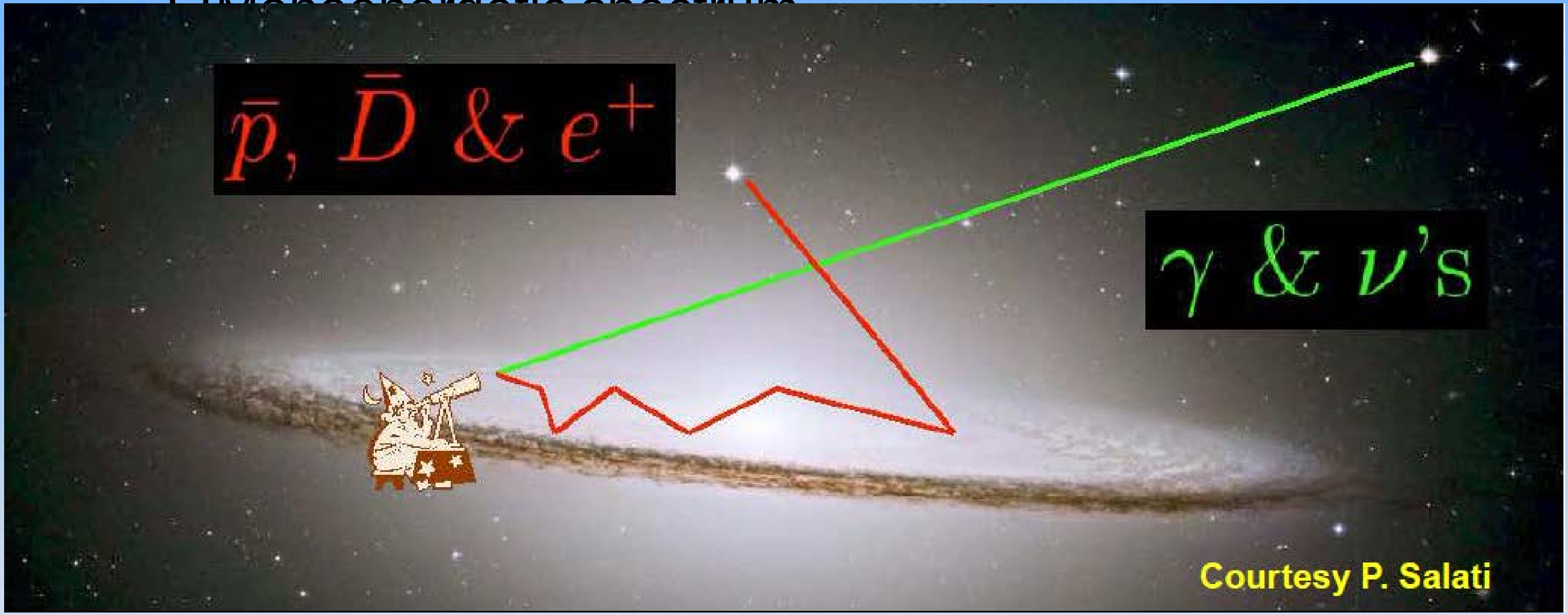




Pamela - 06/2006

# Indirect detection of dark matter -- signals

□Monoenergetic spectrum




definitive signal

# Large High Altitude Air Shower Observatory (LHAASO)

WCD: 4x10⁴m²

μ : 100x400m²

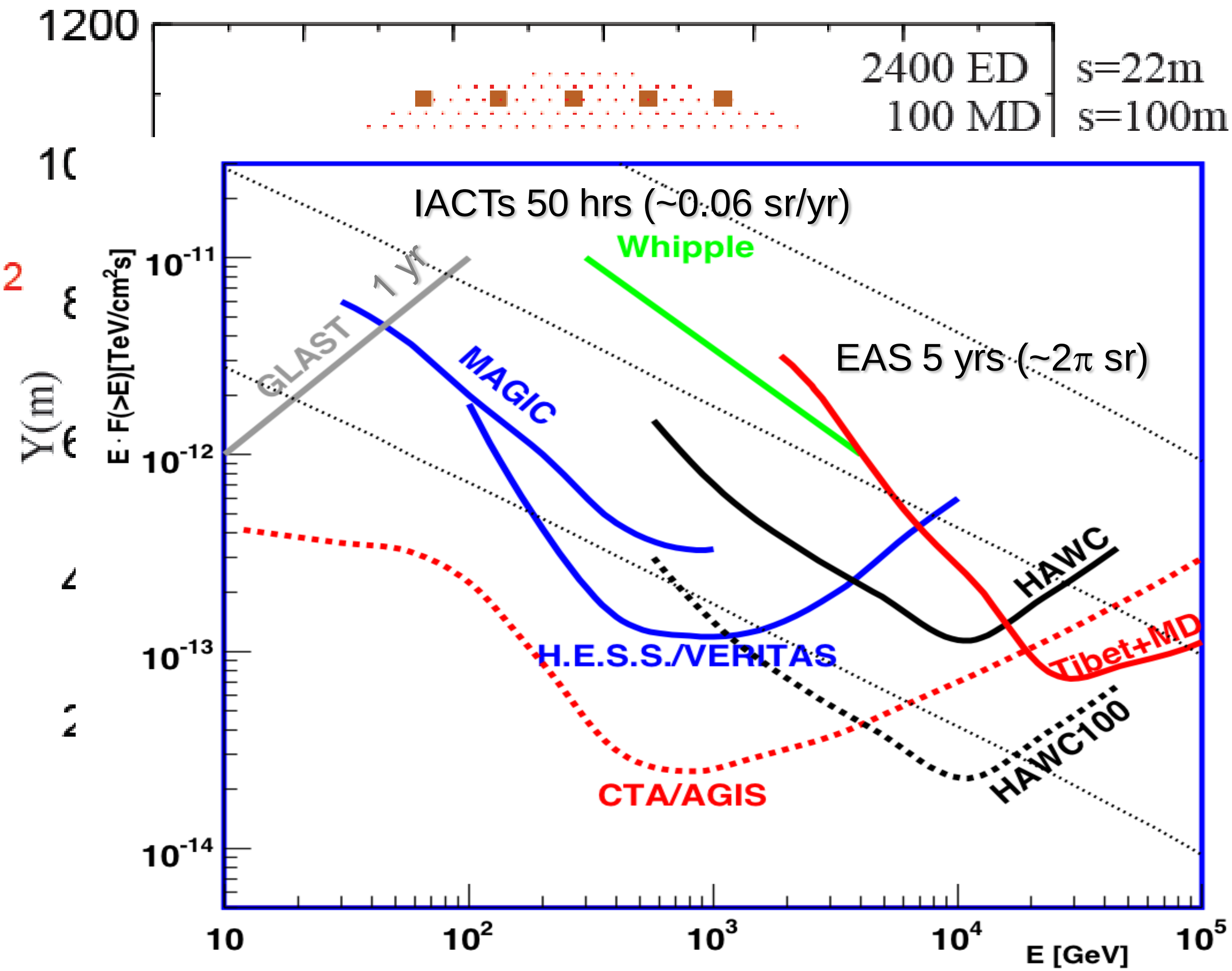
e : 2400x1m²

CT: 28

BD: 1000x1m²

AS+ μ :

ARGO: 10⁴m²

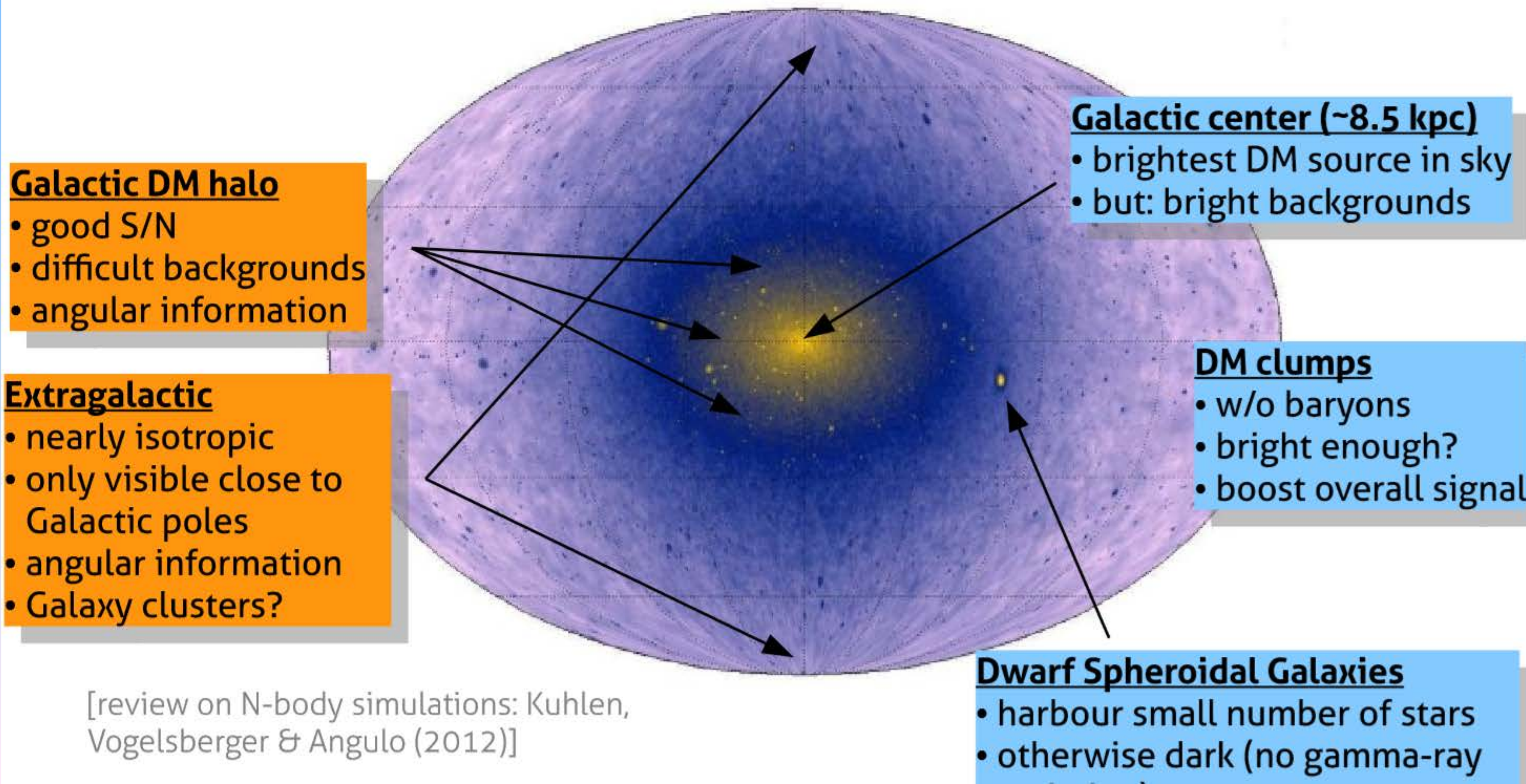


# Gamma rays from DM

## Many potential targets

Signal is approximately proportional to column square density of DM

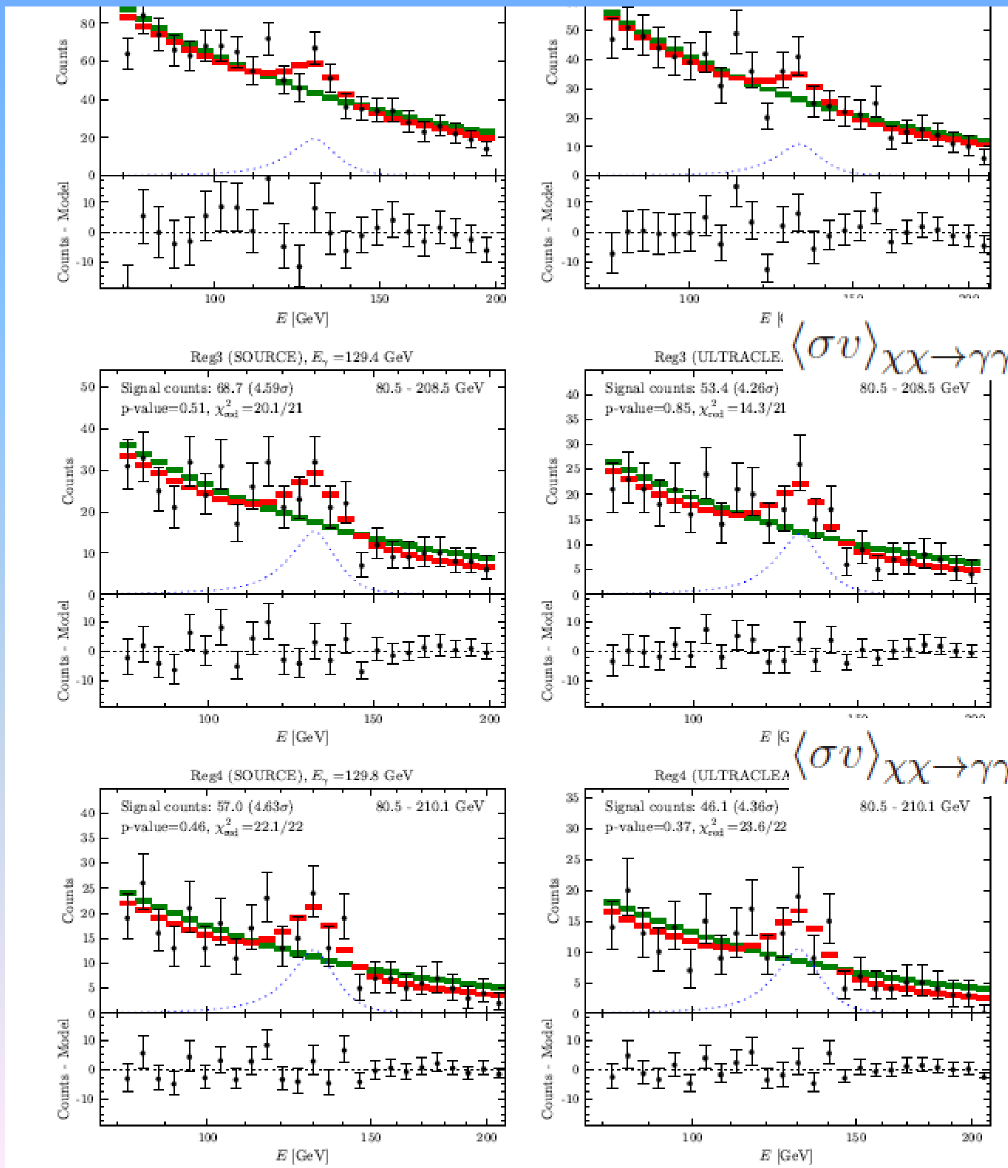
$$\frac{d^2\phi}{d\Omega dE} = \frac{\langle \sigma v_{\rm rel} \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} ds \; \rho(\vec{r}[s,\Omega])^2$$




[review on N-body simulations: Kuhlen, Vogelsberger & Angulo (2012)]

# Fit to the data with line spectra for different DM density profile

Weniger, arXiv:1204.2791



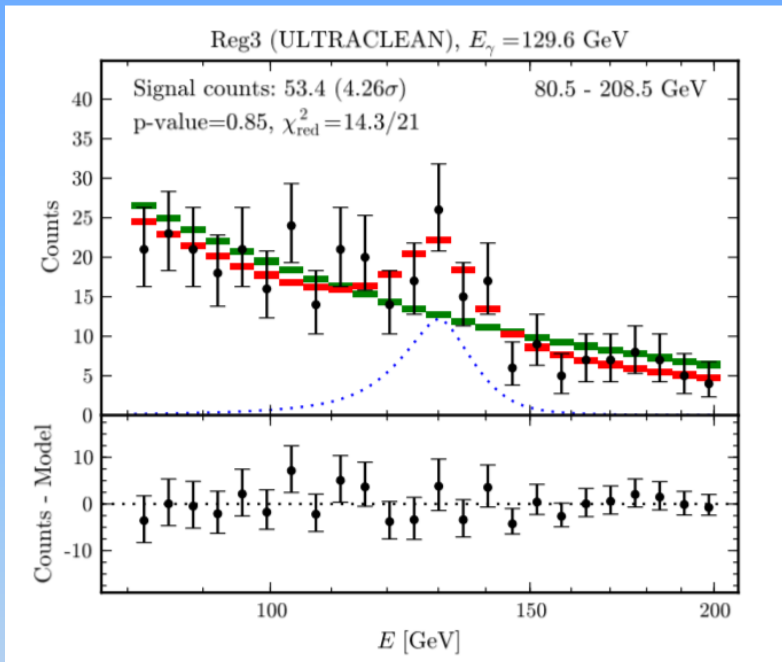

Einasto $$\rho_{\rm dm}(r) \propto \exp\left(-\frac{2}{\alpha_E}\frac{r^{\alpha_E}}{r_s^{\alpha_E}}\right)$$

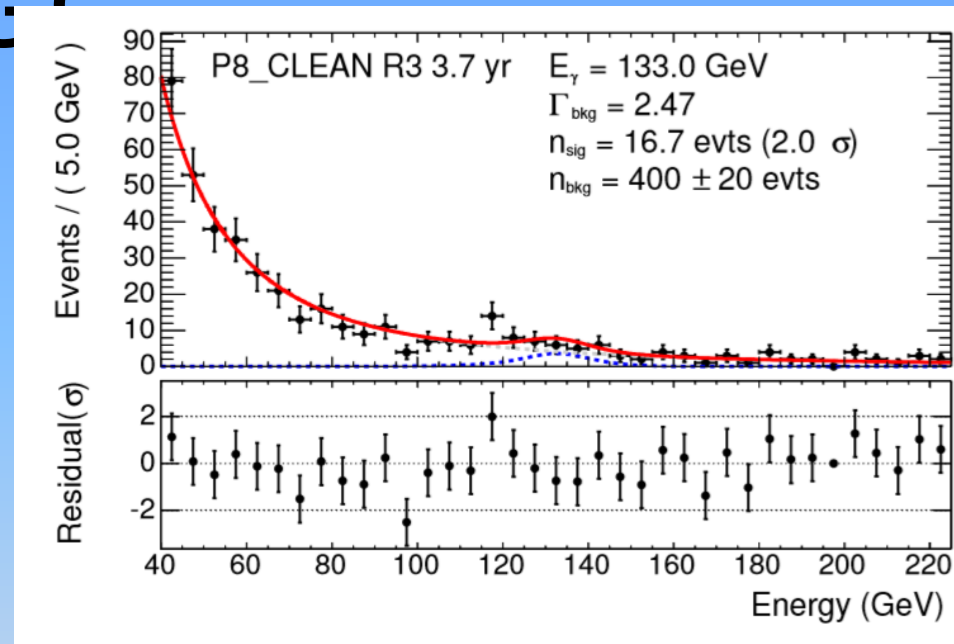
$$\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27}\ {\rm cm^3\ s^{-1}}$$

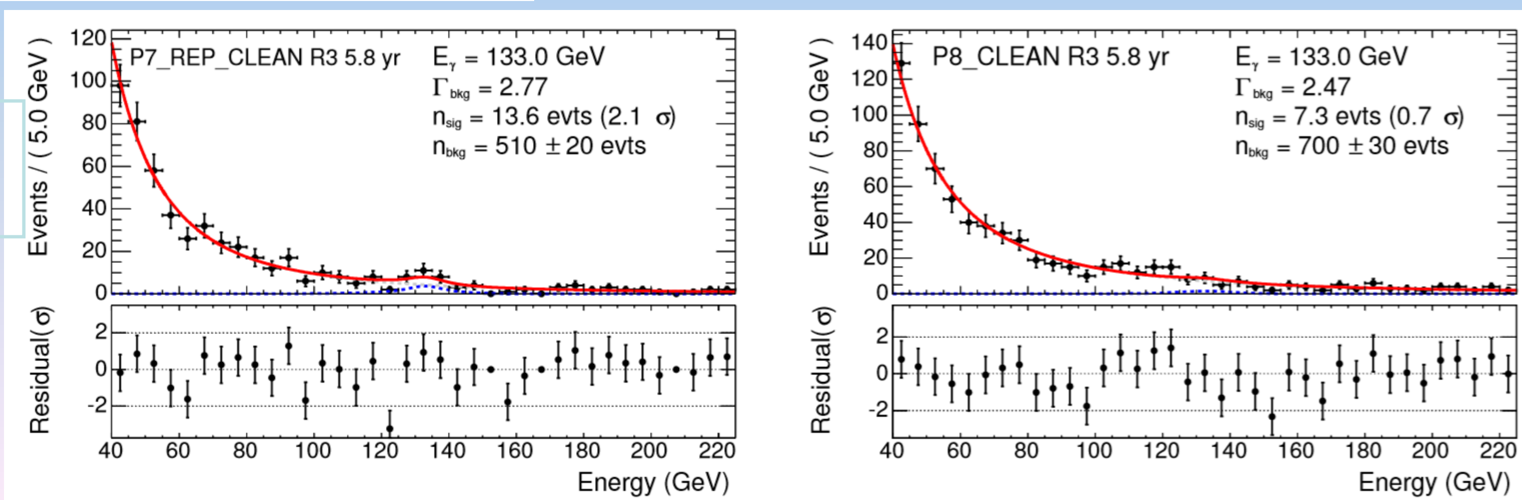
NFW $$\rho_{\rm dm}(r) \propto \frac{1}{(r/r_s)^\alpha\,(1+r/r_s)^{3-\alpha}}$$

$$\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (2.27 \pm 0.57^{+0.32}_{-0.51}) \times 10^{-27}\ {\rm cm^3\ s^{-1}}$$

# 133GeV gamma ray line from GC

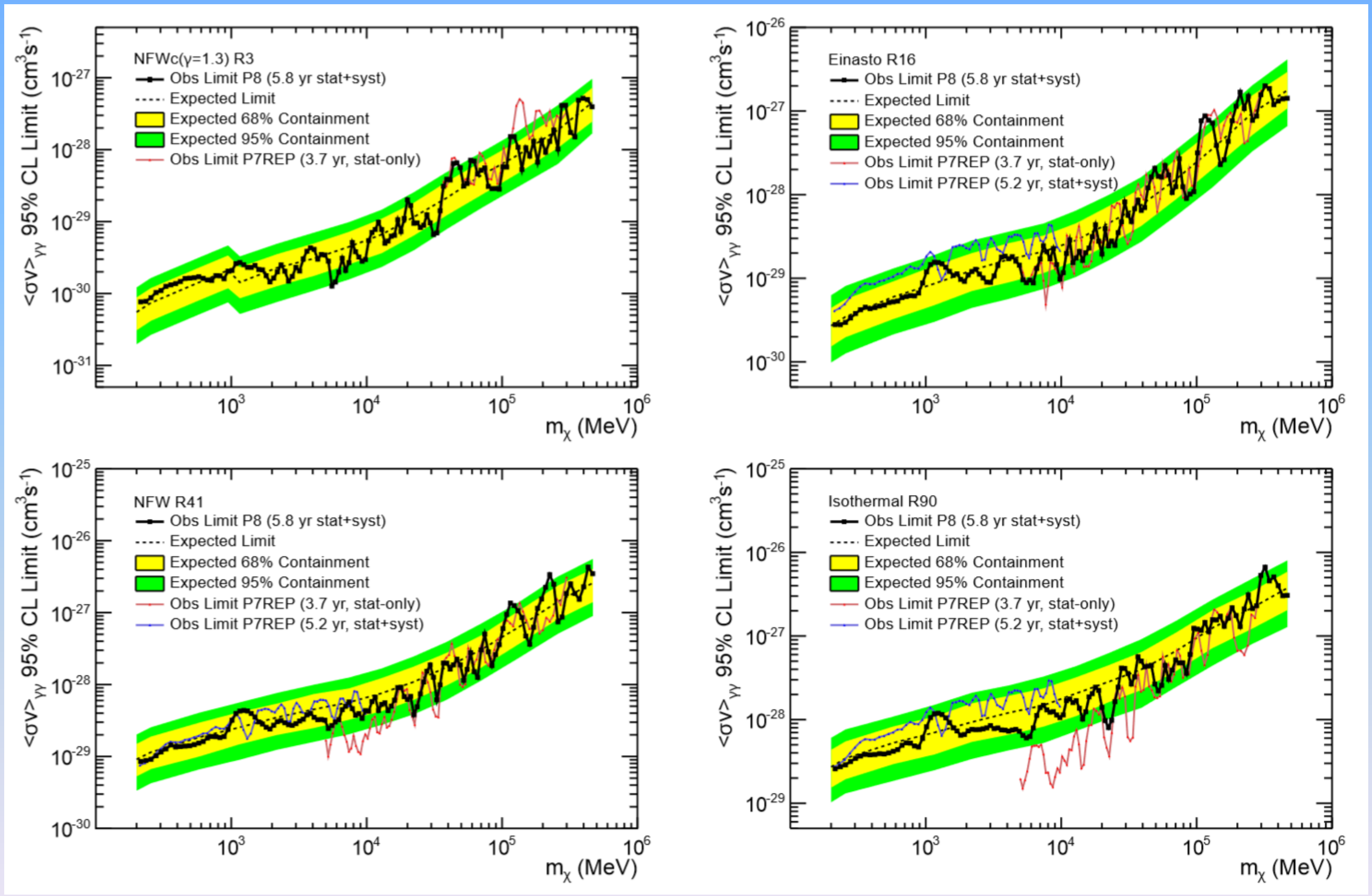



Ackermann et al. 1506. 00013

# New limit on monochromatic gamma



# HESS-II results on gamma-ray lines

**Previous results**

- HESS-I upper limits 500 GeV – 25 TeV

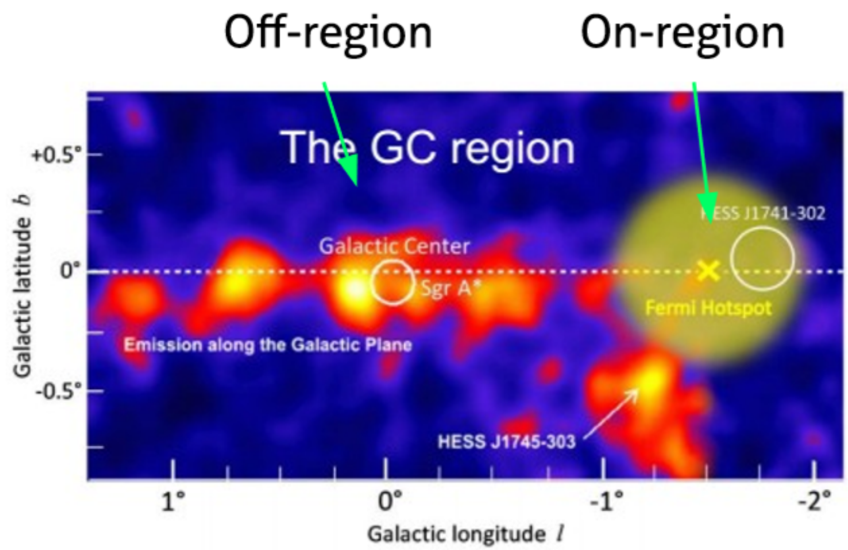
**New preliminary HESS-II results**

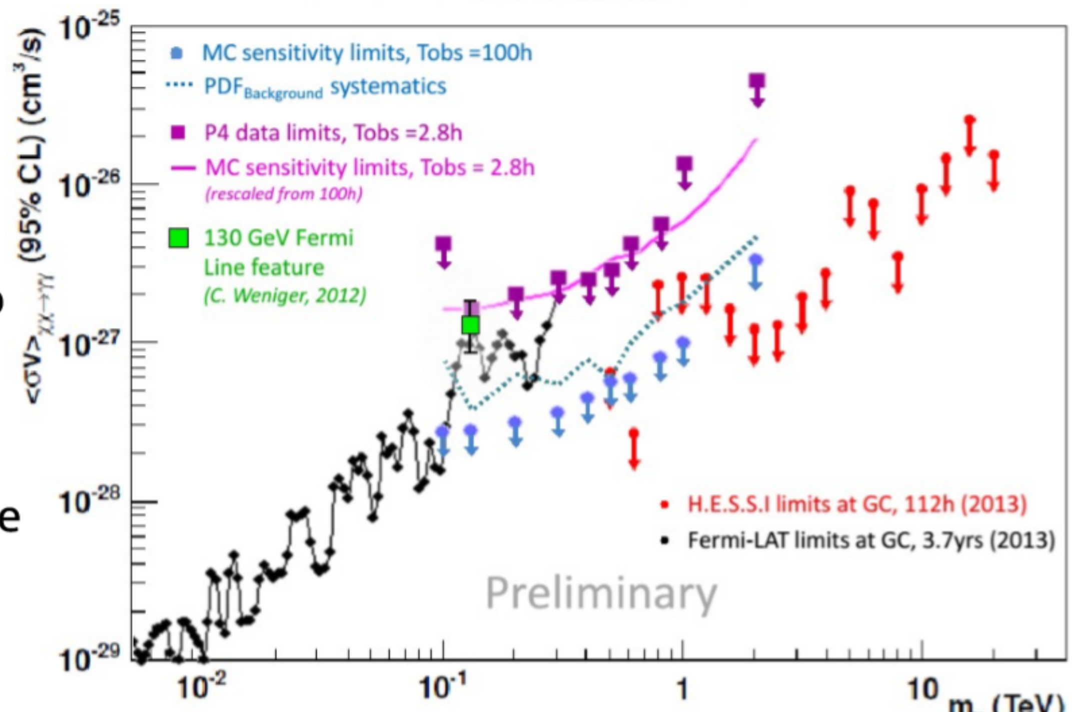
- Search in "Fermi hot spot" (l=-1.5 deg ; b=0 deg) 100 GeV – 2 TeV
- Preliminary results using 2.8h data (20h available in total)
- Unbinned spectral analysis
- "Off-region" for BG estimates is Galactic center

- Upper limits come close to "Fermi line"
- Projected 100h limits will "close gap between HESS-I and Fermi limits"

**Remember**

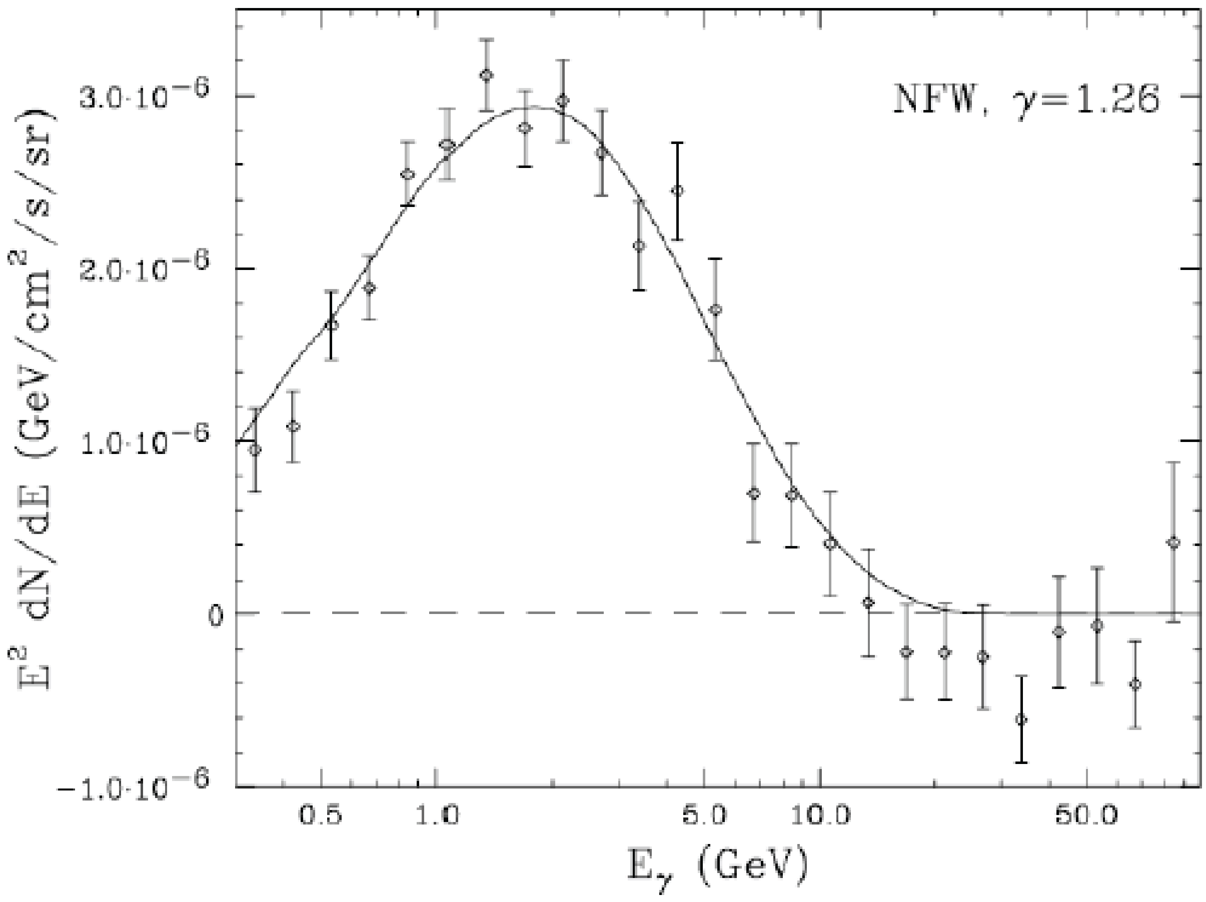
- DM interpretation of 130 GeV feature already in strong conflict with Fermi LAT pass 8 data (> 3 sigma)



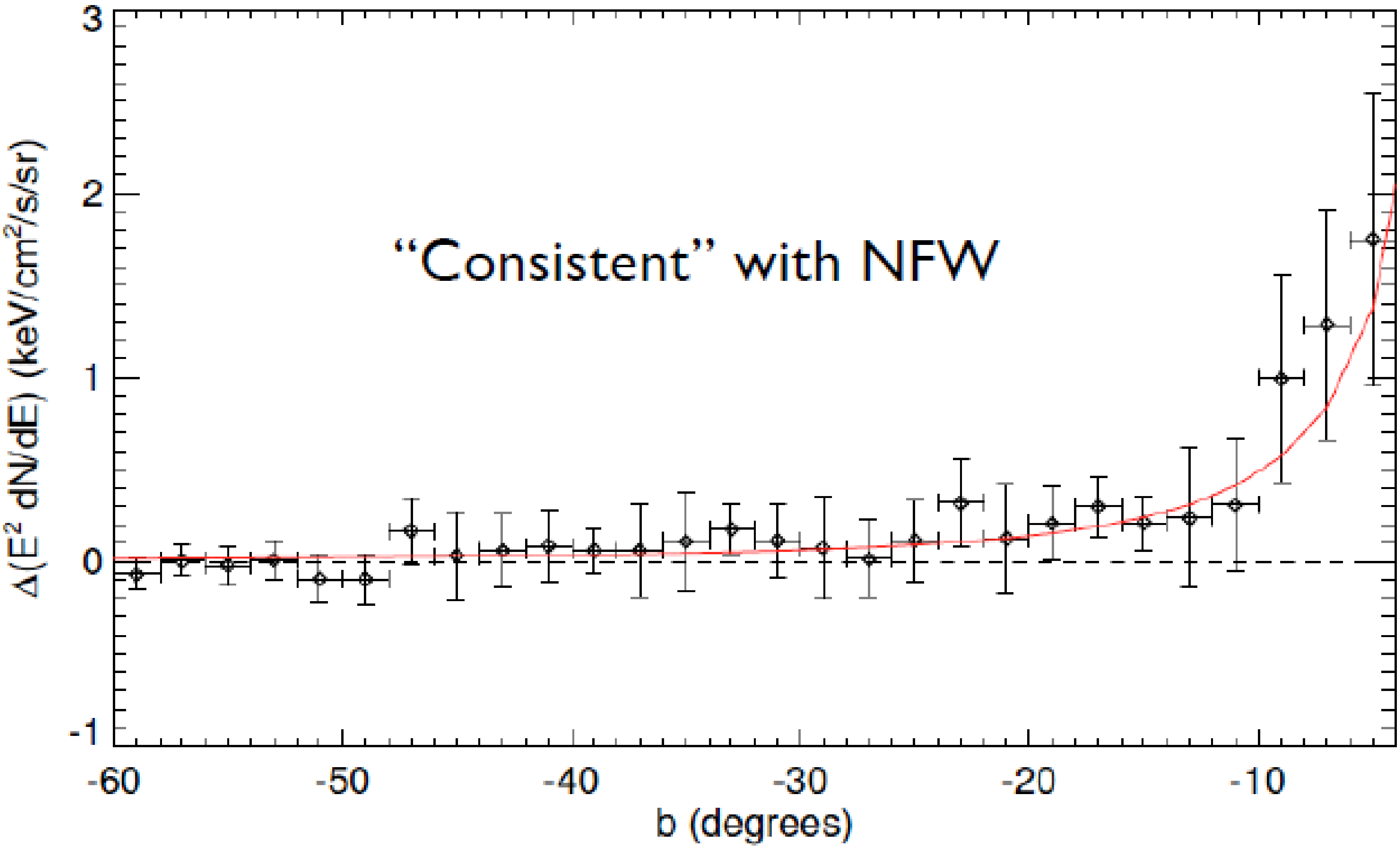

Kieffer+, HESS coll. ICRC 2015

# GeV excess from the Galactic center




A ~35 GeV dark matter particle annihilating to bbar

$$\sigma v = 1.7 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}\ \times [(0.3\,\mathrm{GeV}/\mathrm{cm}^3)/\rho_{\mathrm{local}}]^2$$



"Consistent" with NFW
Δ(E² dN/dE) (keV/cm²/s/sr)
b (degrees)
3
2
1
0
-1
-60
-50
-40
-30
-20
-10

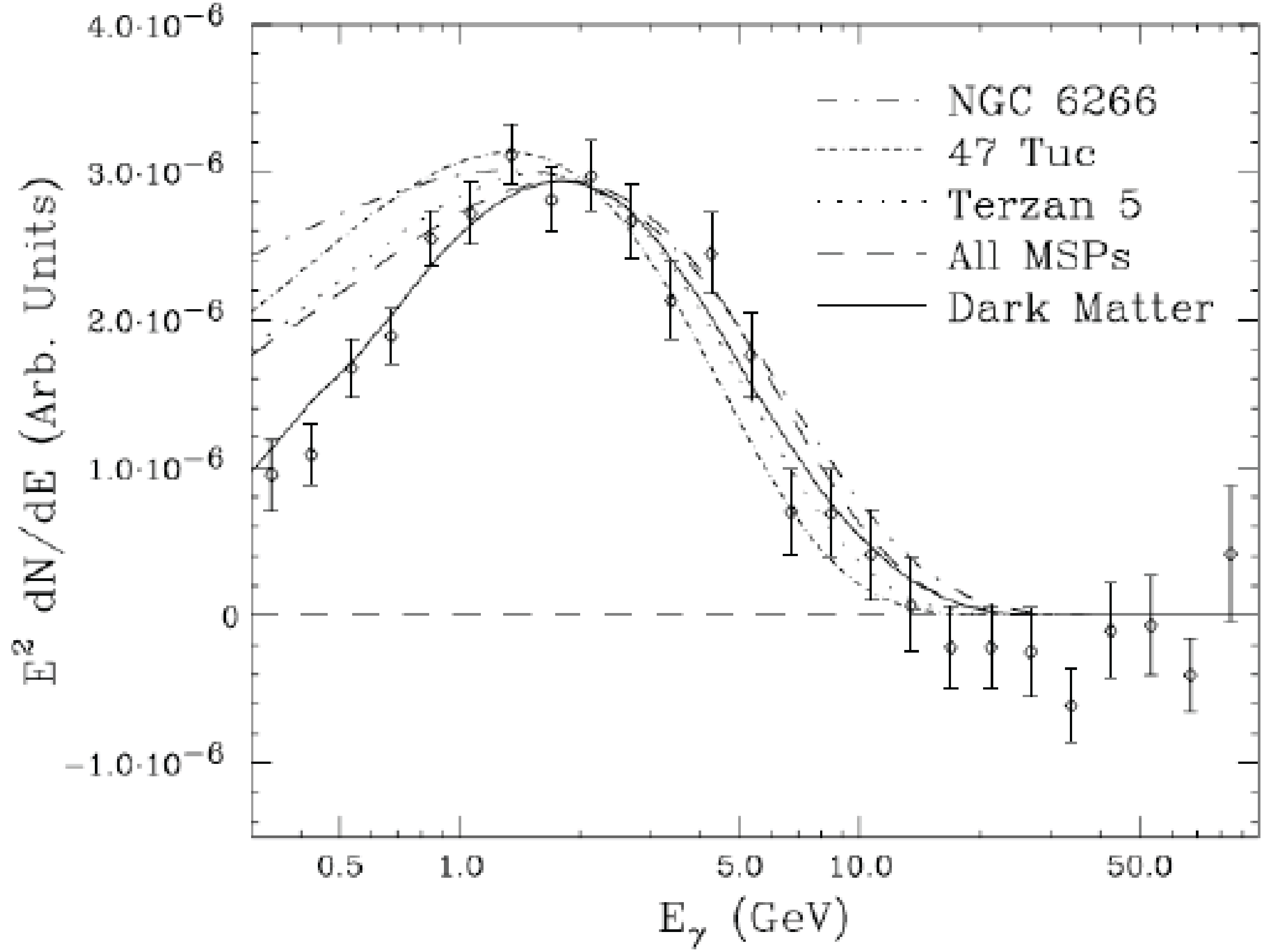
# Statistical significant

~10^4 photons per square meter, per year (>1 GeV, within 10° of the Galactic Center)

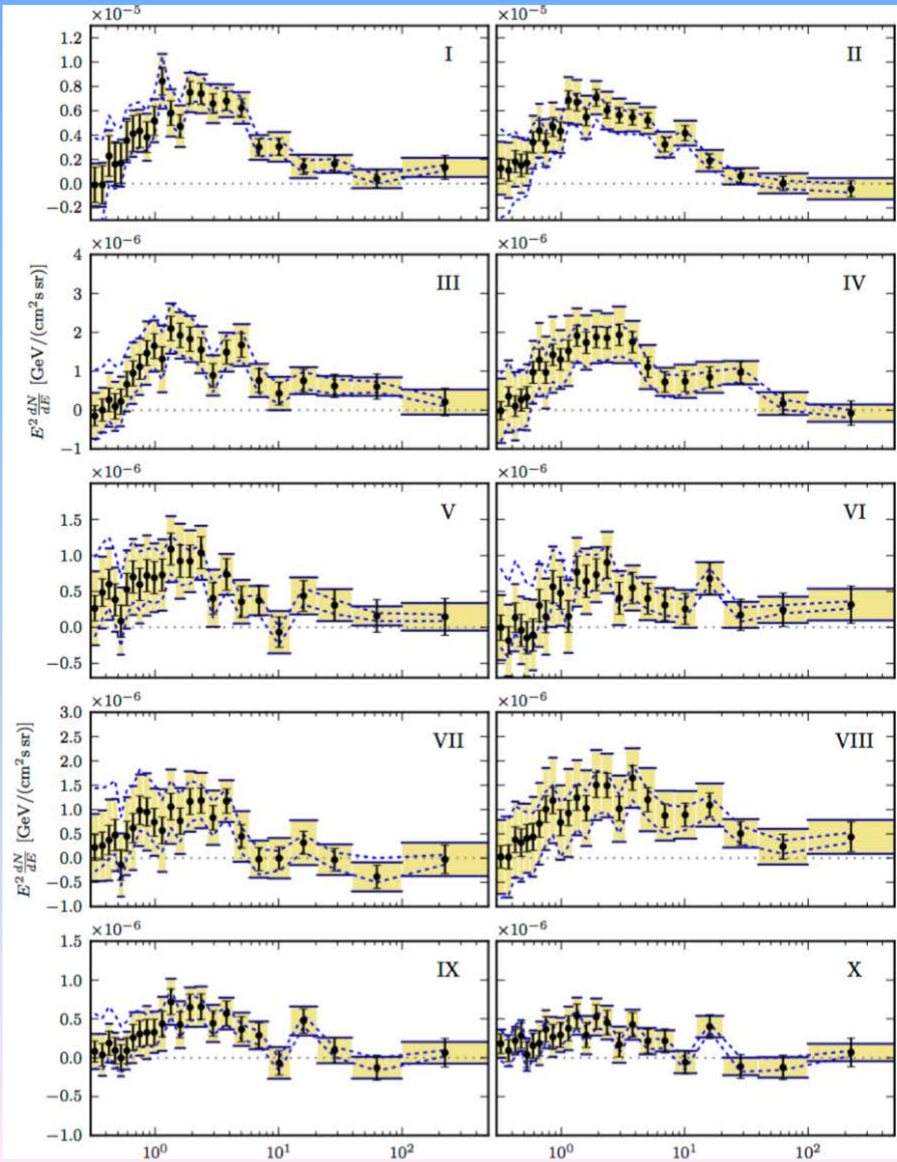
- In our Inner Galaxy analysis, the quality of the best-fit found with a dark matter component improves over the best-fit without a dark matter component by over 40 $\sigma$

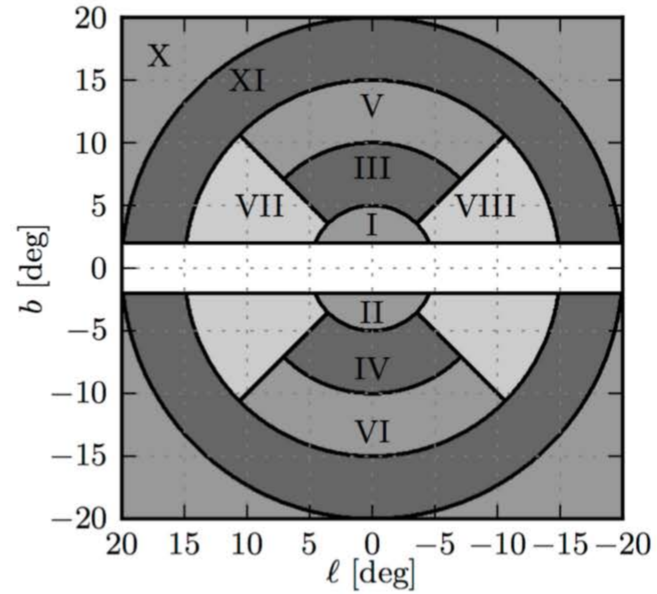
- Studying significant details becomes possible (spectral, morphology...)

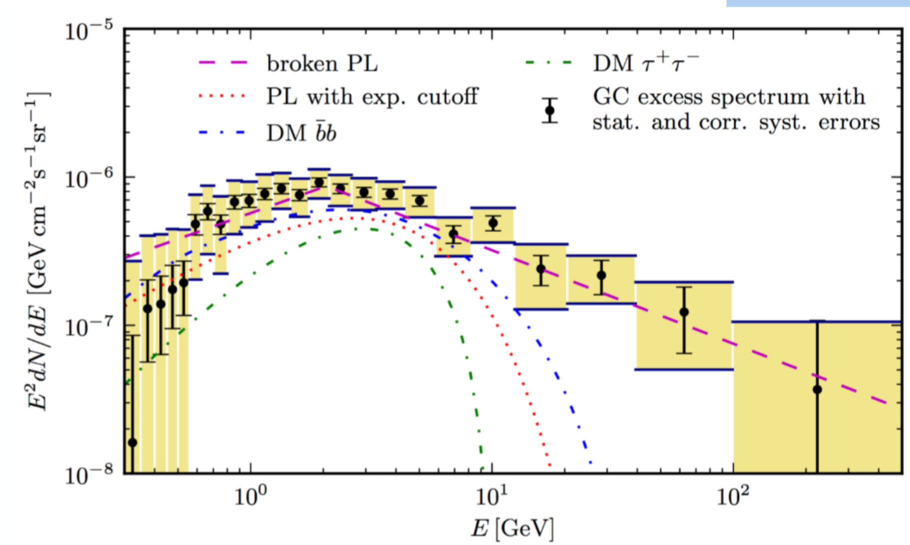
# Sub-GeV is the key!



# Gamma ray excess from the GC



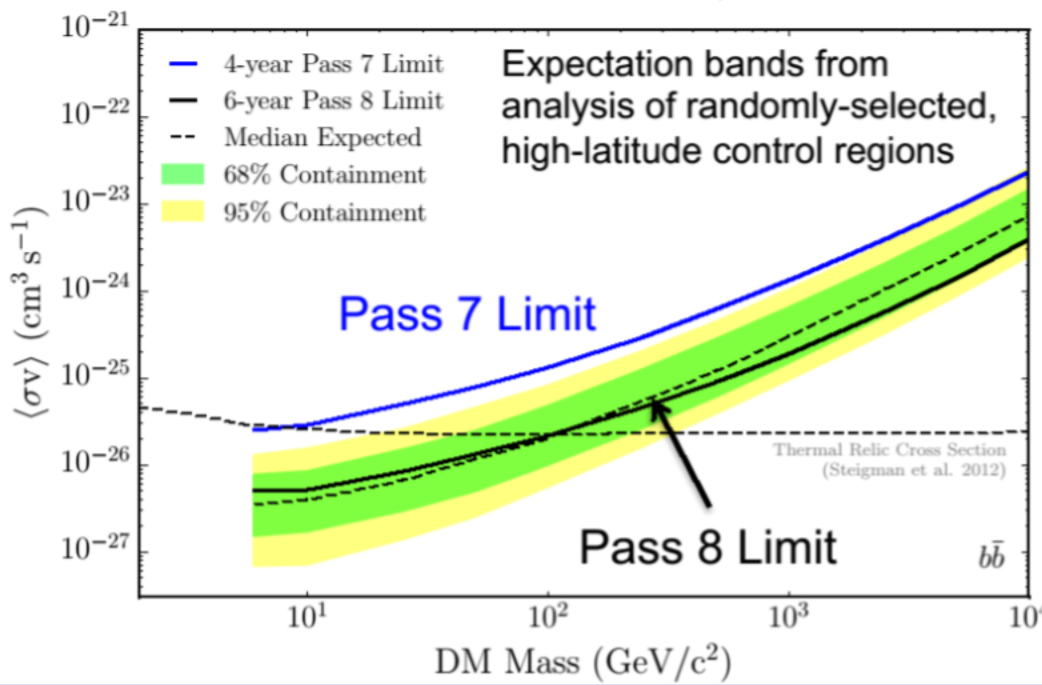
# Constraint from dwarf galaxies

## Current situation

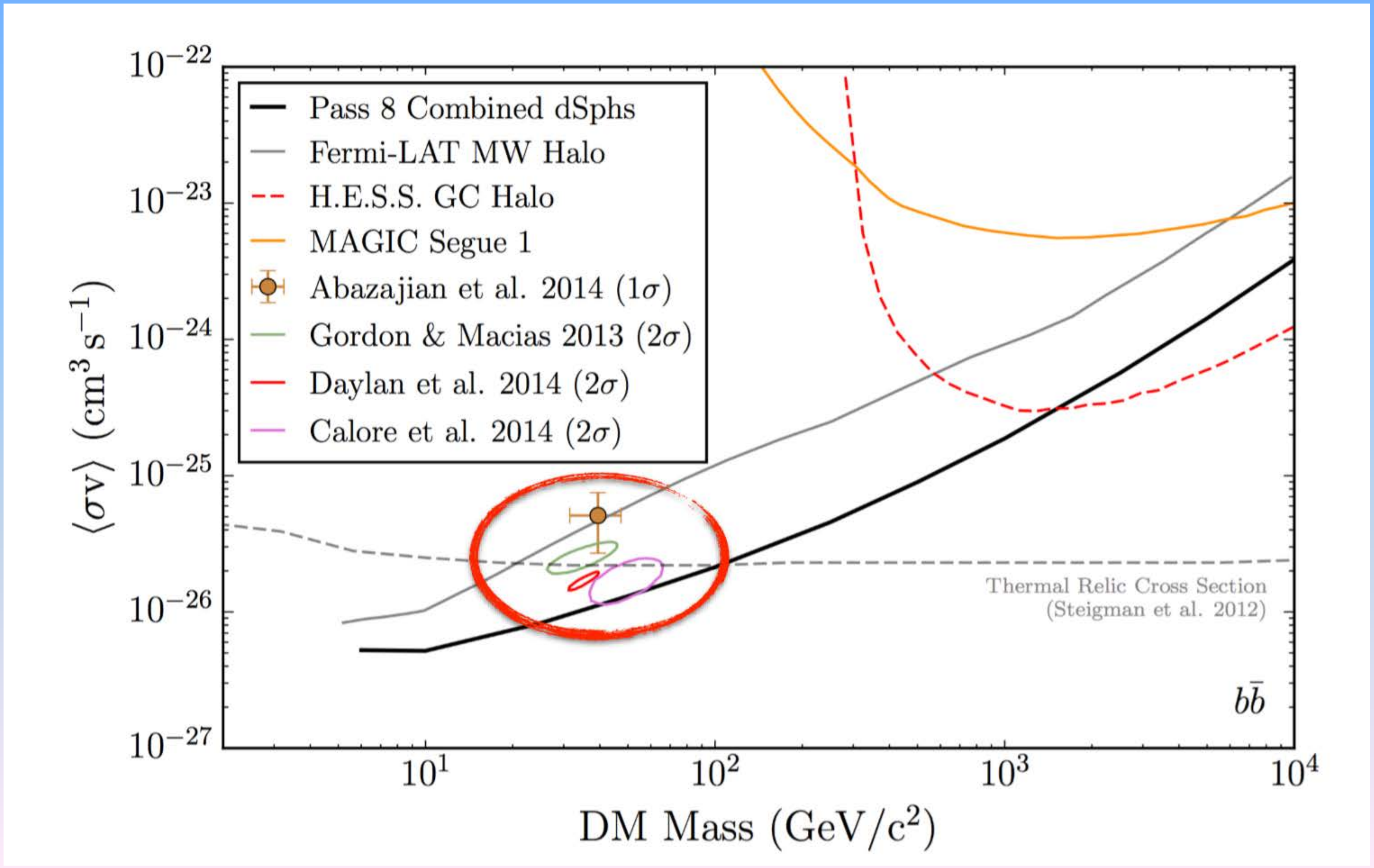
Ackermann et al. 2015, arXiv:1503.02641

**Limits based on 15 dSphs (not including DES candidates)**

- Pass 8: Released June 24 this year!
- Improvements:
  - 4 → 6 years data
  - Pass 7 → pass 8
  - Including PSF quality in fit
- Limits in very good agreement with expectations → no indication for signal from



# The GC excess due to DM annihilaiton seems be disfavored



# HESS results

## Preliminary HESS-I results (and HESS-II projections)

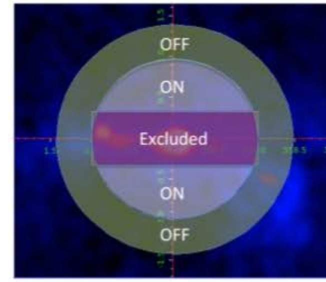
**Results**

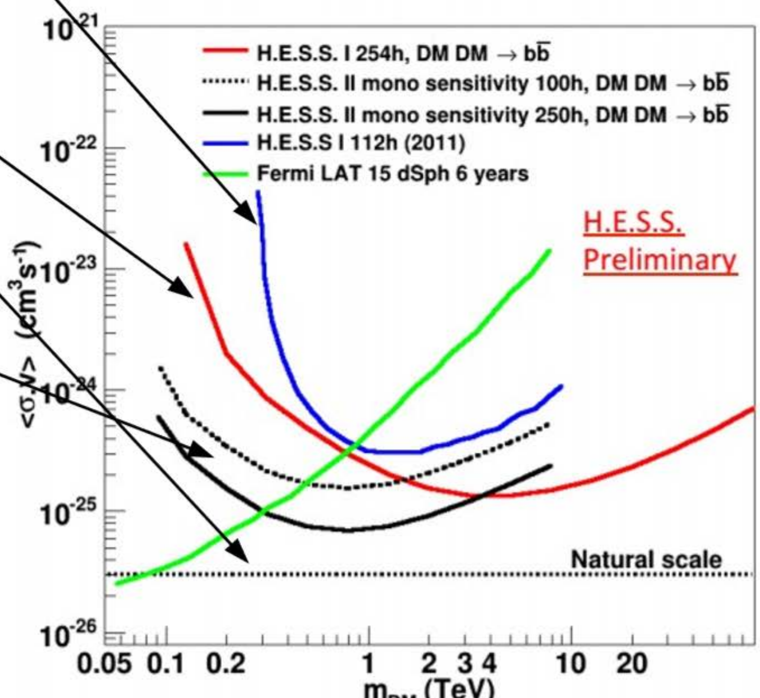
- Previous results: 2011 PRL (112h), using Tasitiomi signal spectrum
- **Now**:
  - 254h
  - full 2D spectra + spatial likelihood
  - realistic signal spectra

→ Significant improvement of limits
→ tau+ tau- limits reach thermal cross-section

- **Projections for HESS-II**
  - Improvement by factor 5 and more below 1 TeV

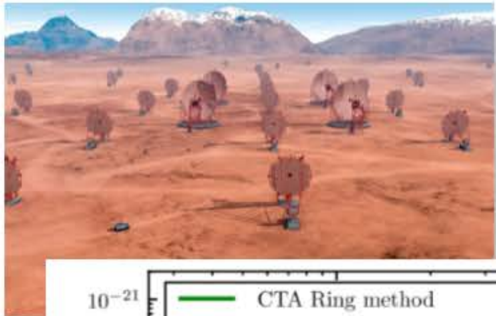
On & Off regions



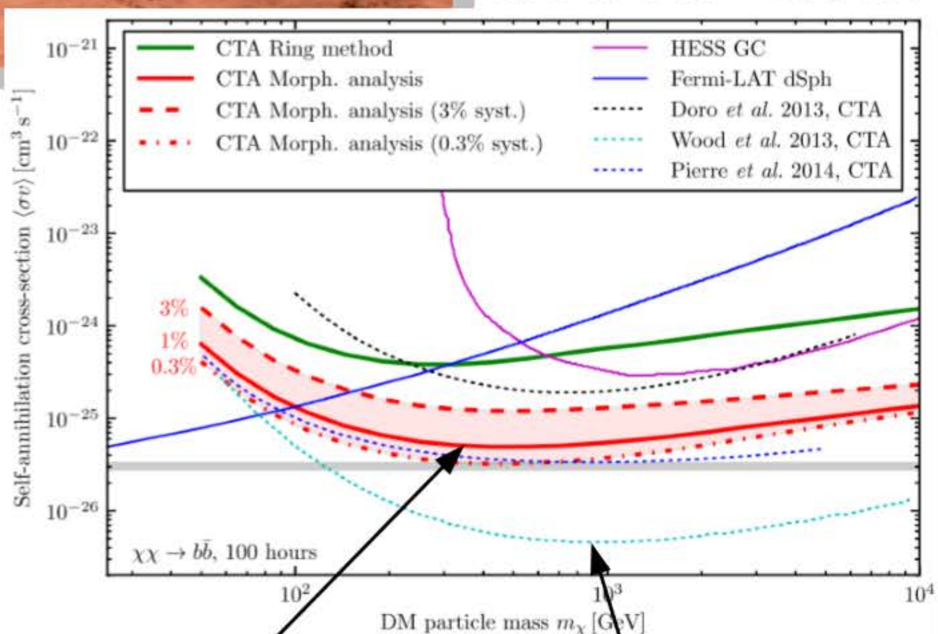

Lefranc+, HESS coll., ICRC 2015

# Indirect detection prospects for the next years



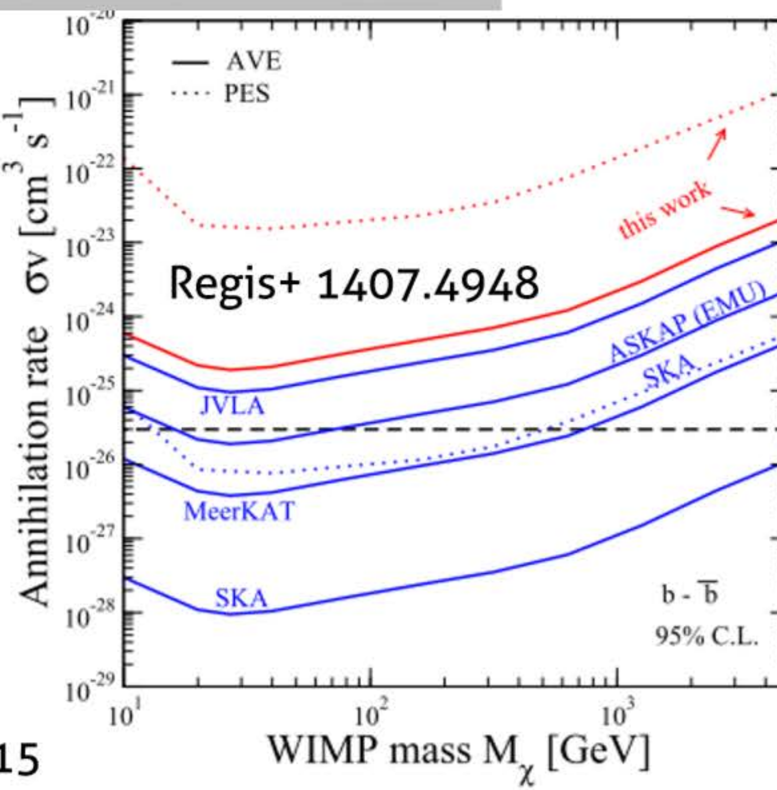
cta
cherenkov telescope array

Tens of GeV – 100 TeV




SKA
SQUARE KILOMETRE ARRAY

50 Mhz – 14 GHz




Regis+ 1407.4948

Silverwood+ 1408.4131
(1% uncorr. systematics)

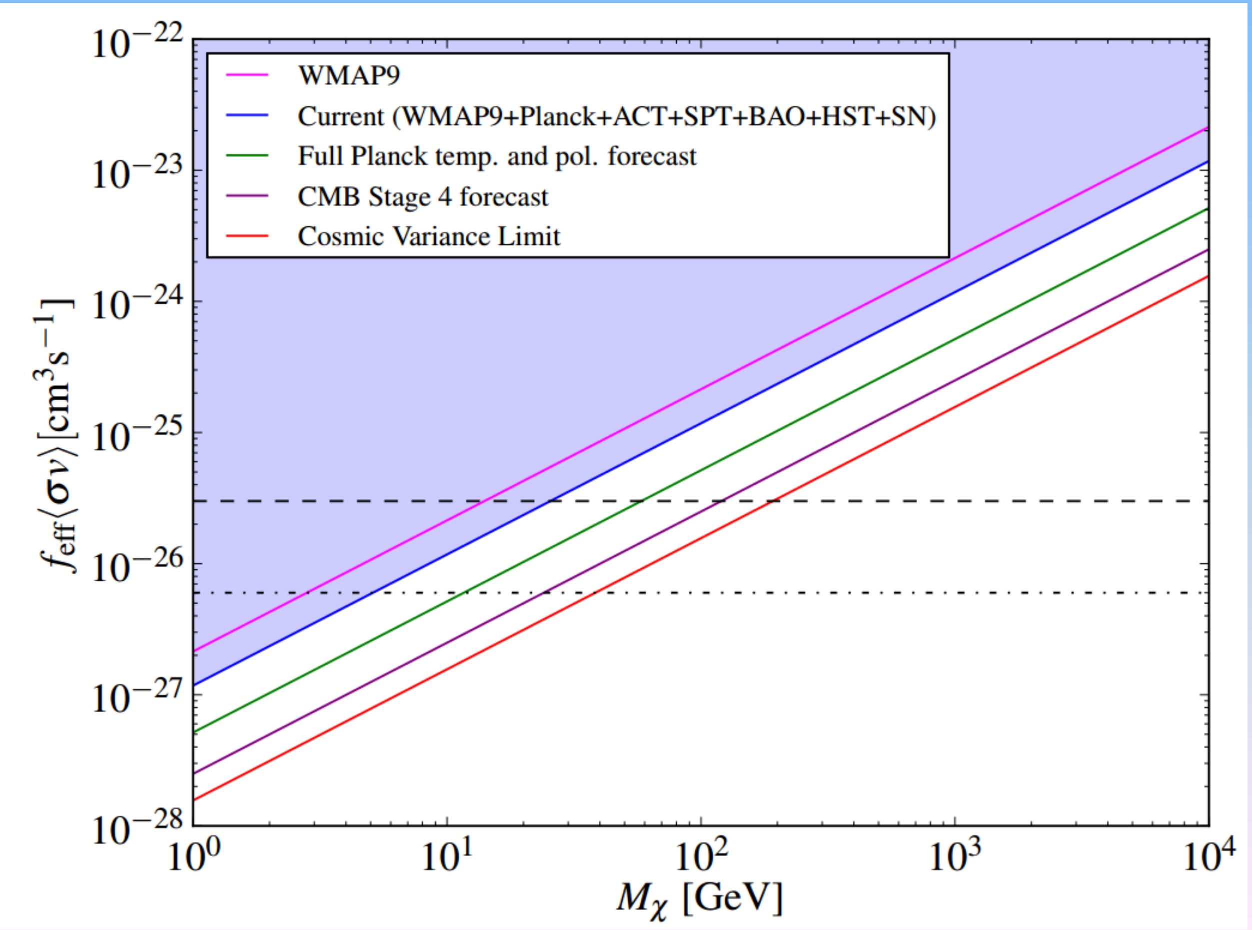
CTA coll. (stat. only)
Wood+ 1305.0302
Similar to J. Carr ICRC 2015

Note: Real instr. systematics are *correlated*,
detailed studies are ongoing in CTA coll.

# Constraints from CMB

- DM annihilation heats and ionizes the photon-baryon plasma at z~1000, constrained by WMAP and Planck

T.R. Slatyer et al.,
**1310.3815**



# Constraints on the minimal subhalos by observations of clusters

A. Pinzke et al.,
**0905.1948**

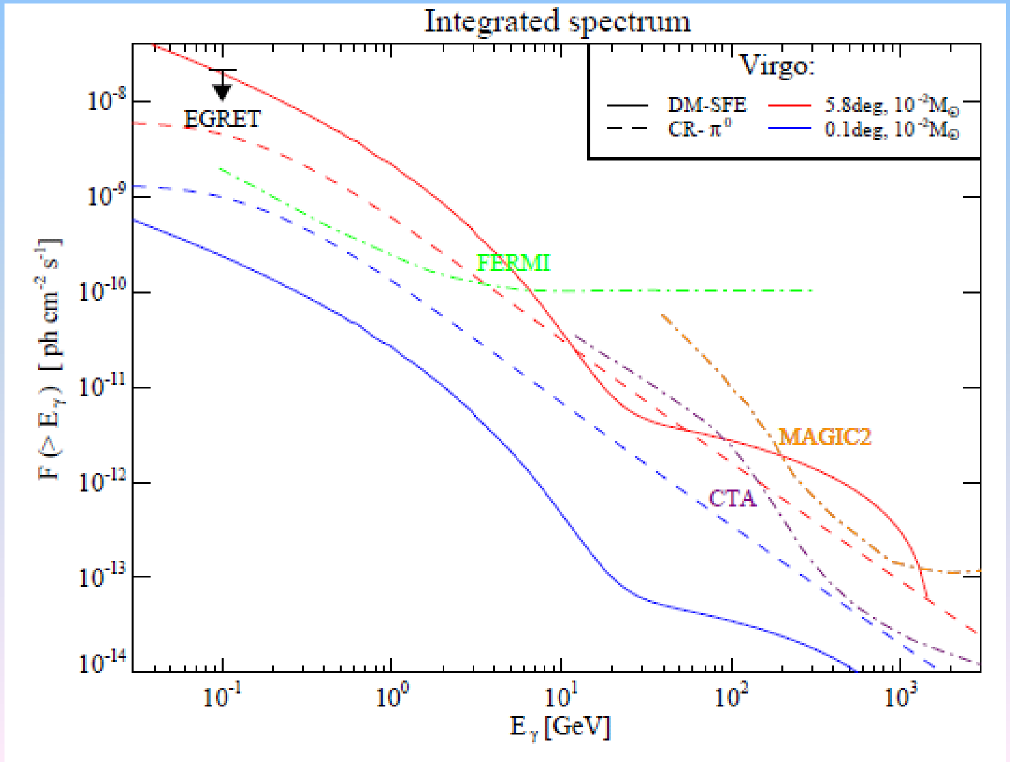
- Standard CDM predicts the minimal subhalos $M_{\rm sub} = 10^{-6}\,{\rm M}_\odot$
- Observation constrains

$M_{\rm lim} = 10^{-2}\,{\rm M}_\odot.$

- Fermi limit to

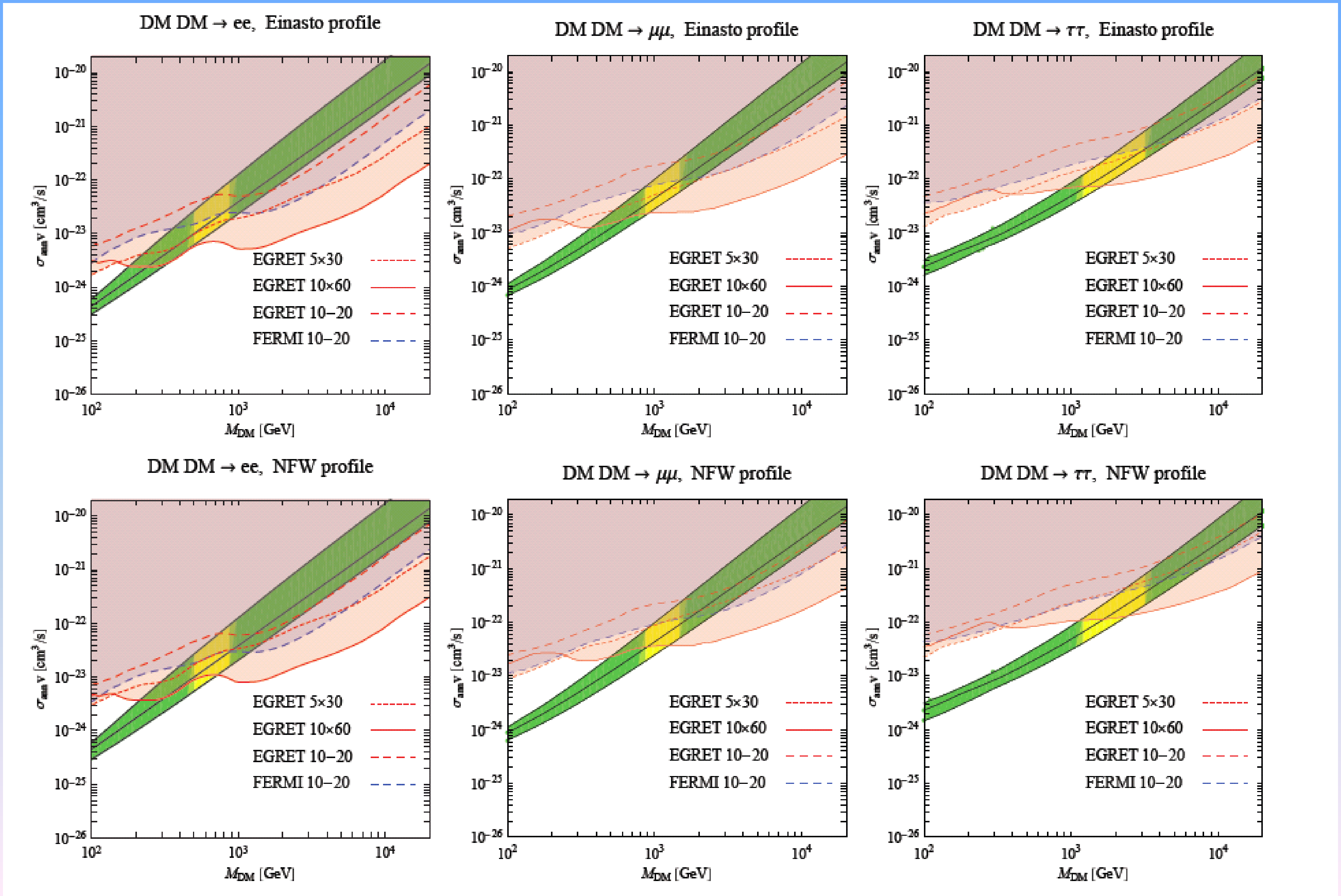
$> 10^3\,{\rm M}_\odot$:

- DM is warm



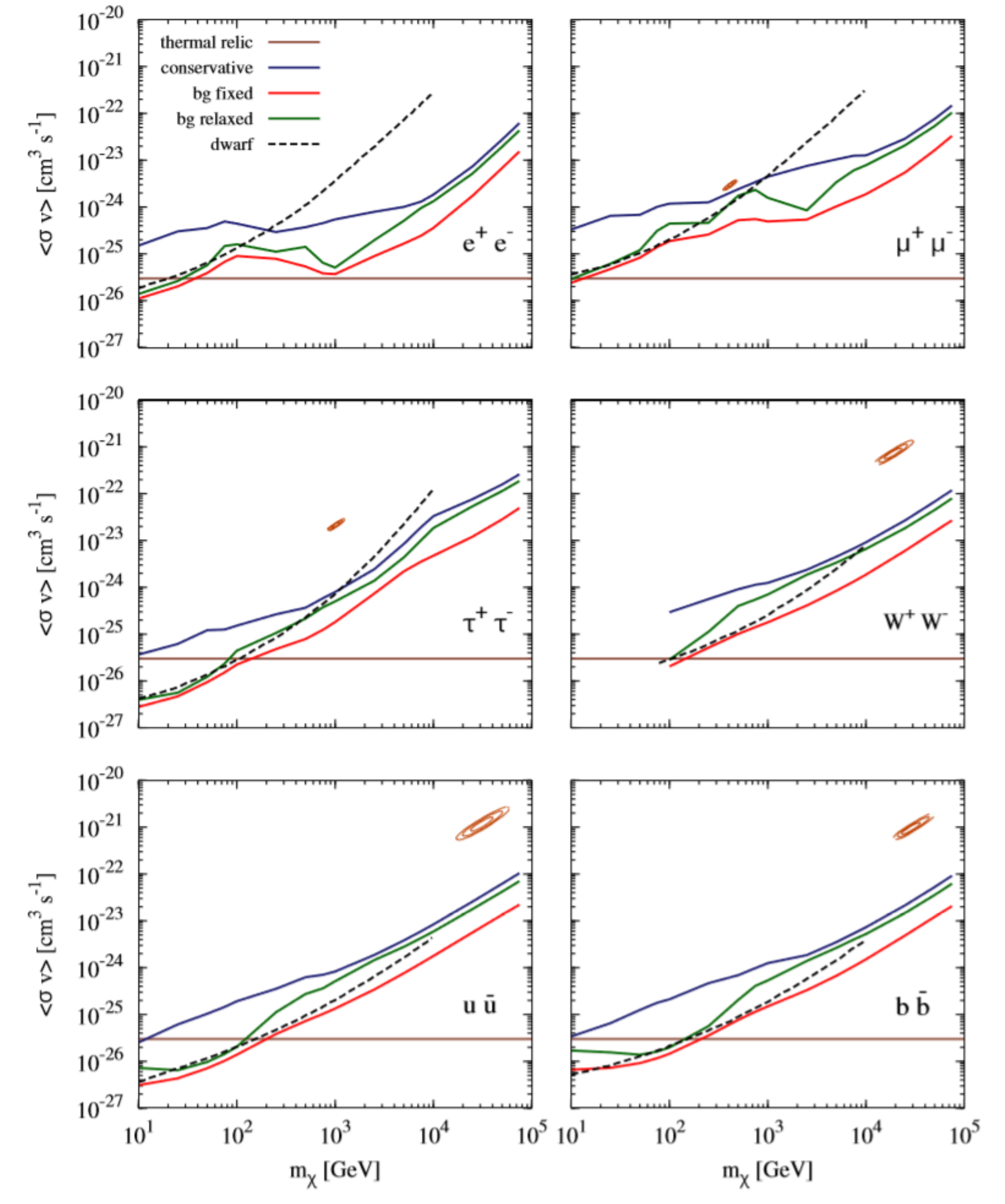
# Constraint by Galactic diffuse gamma rays

M. Cirelli et al.,
**0904.3830**



# Constraints from extragalactic diffuse gamma rays

Liu W. et al., **1602.01012**



# Neutrinos from the sun or the earth

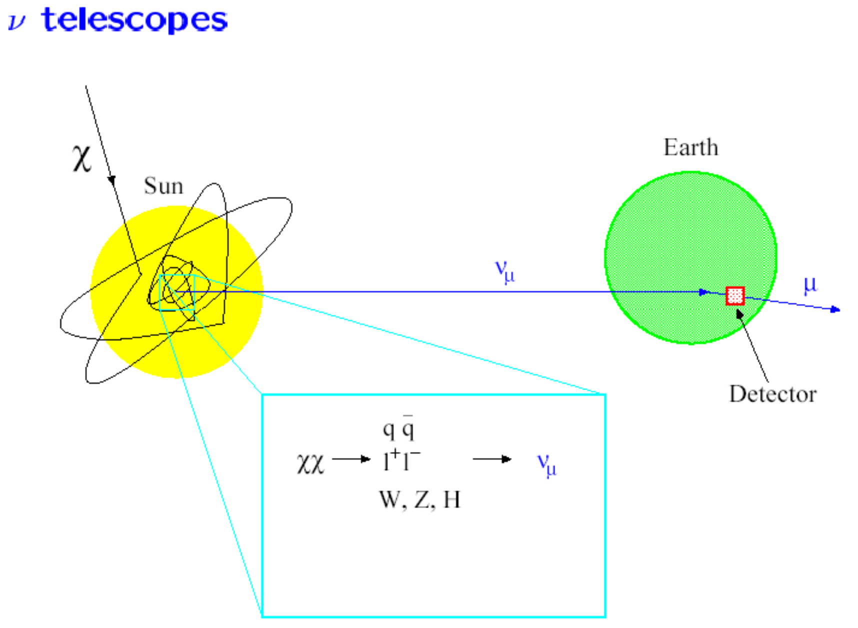
- Density at the solar center is determined by the scattering, insensitive to the local density

$$\dot{N} = C_\odot - C_A N^2 - C_E N$$

$$C_\odot \sim 10^{20}\mathrm{s}^{-1}\left(\frac{\rho_\chi}{0.3\ \mathrm{GeV}\cdot\mathrm{cm}^{-3}}\right)\left(\frac{270\ \mathrm{km}\cdot\mathrm{s}^{-1}}{\bar{v}}\right)^3 \times\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2\left(\frac{\sigma_{SD}^{\chi H}+\sigma_{SI}^{\chi H}+\sum_i \xi_i \sigma^{\chi N_i}}{10^{-42}\mathrm{cm}^2}\right)$$

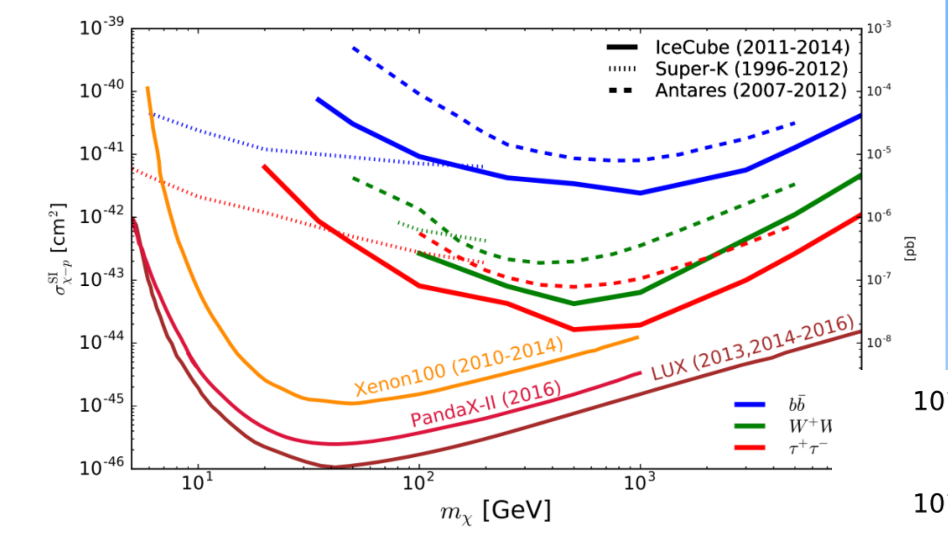
$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \simeq \frac{C_\odot}{2}\frac{1}{4\pi R_{SE}^2}\sum_i Br_i\left(\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\right)_i$$

- The present data gives constr -aints on the parameter space
- IceCube can cover most parar

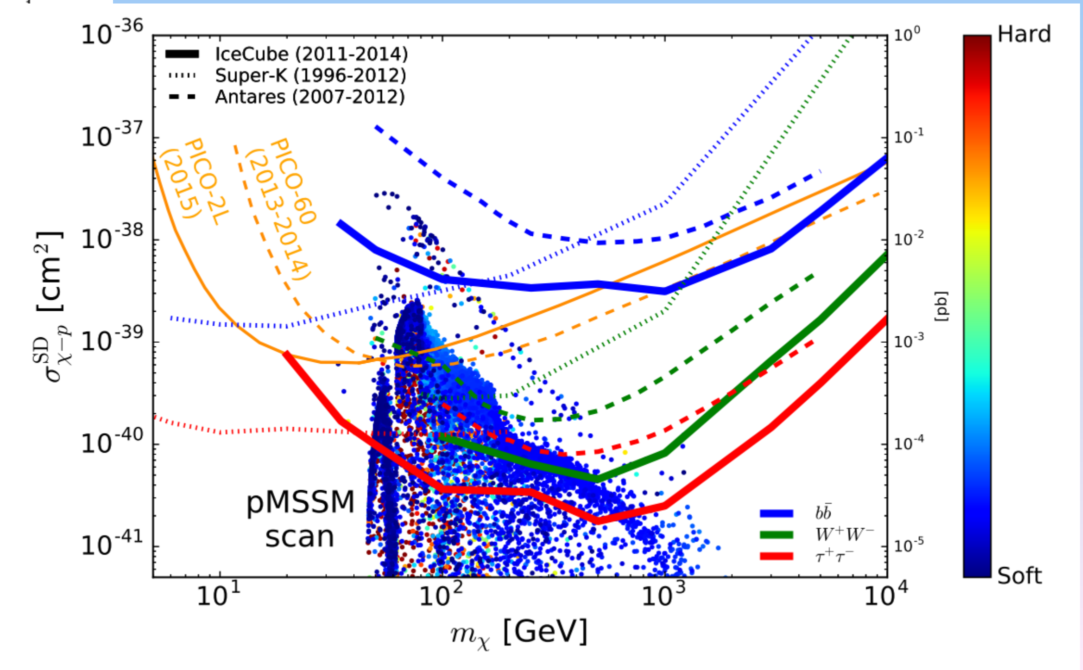


# Constraints from the neutrino detection

- Neutrinos from the Sun

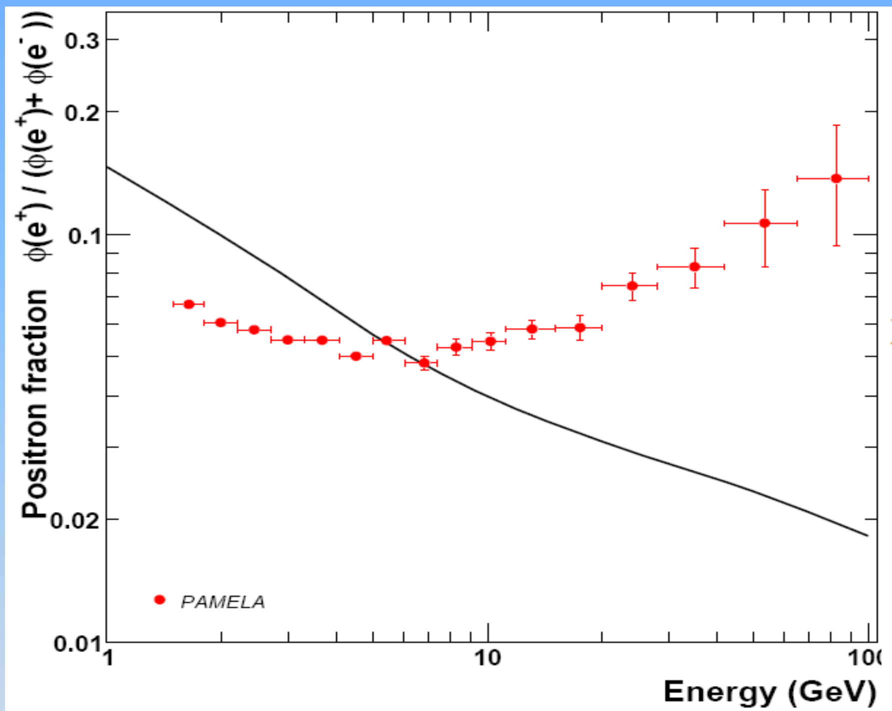



Arxiv: 1612.05949



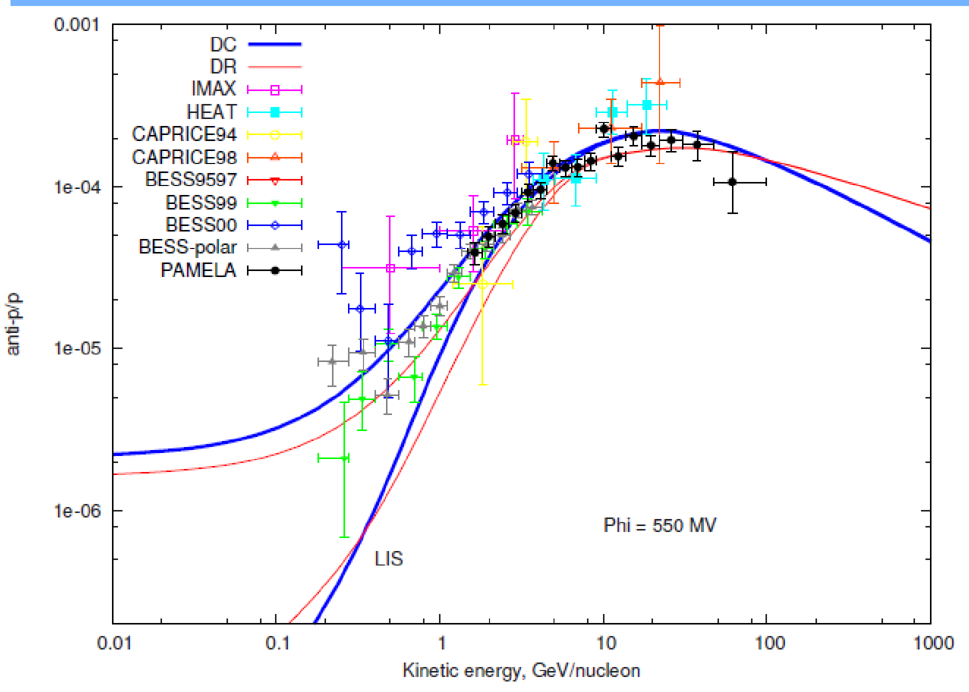
# PAMELA results of antiparticles in cosmic rays

## Positron fraction




*Nature 458, 607 (2009)*

## Antiproton fraction

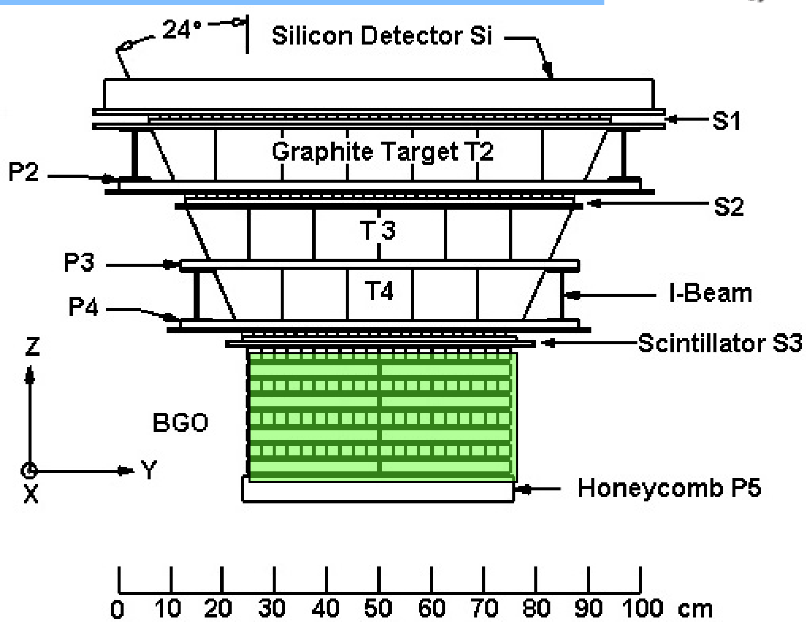


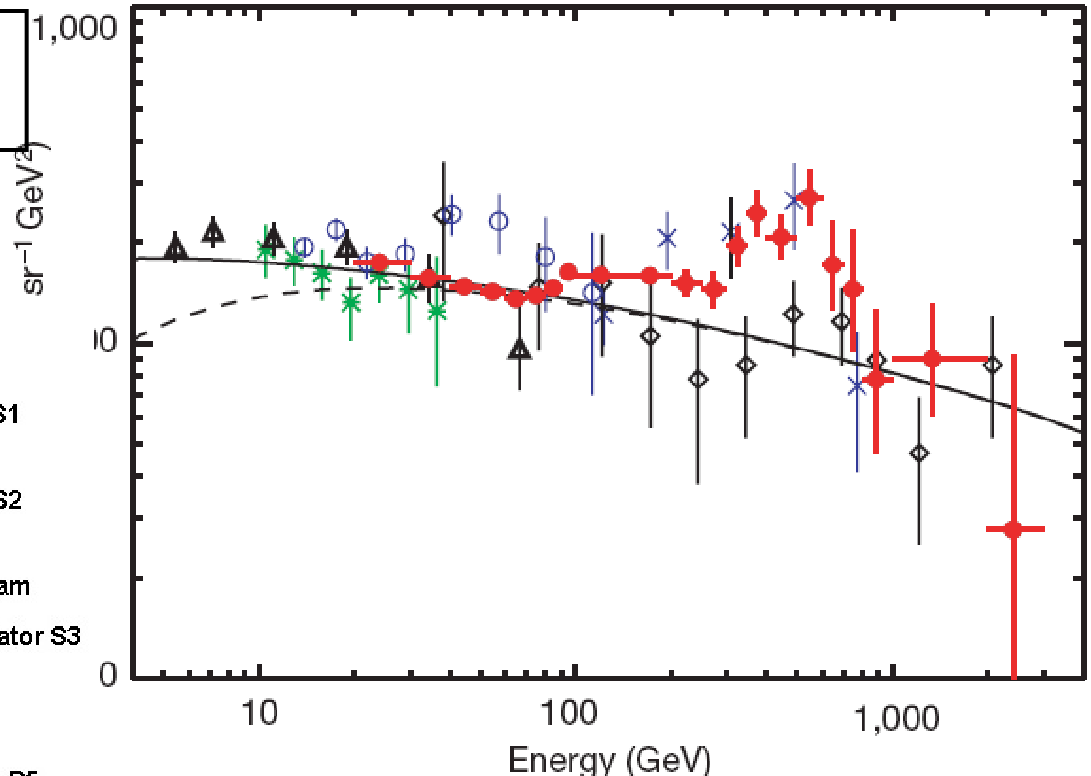

Phys.Rev.Lett.102:051101,2009

>1000 citations after submitted on 28th Oct. 2008

# Bump at the electron/positron spectrum

Chang et al.
Nature456, 362 2008

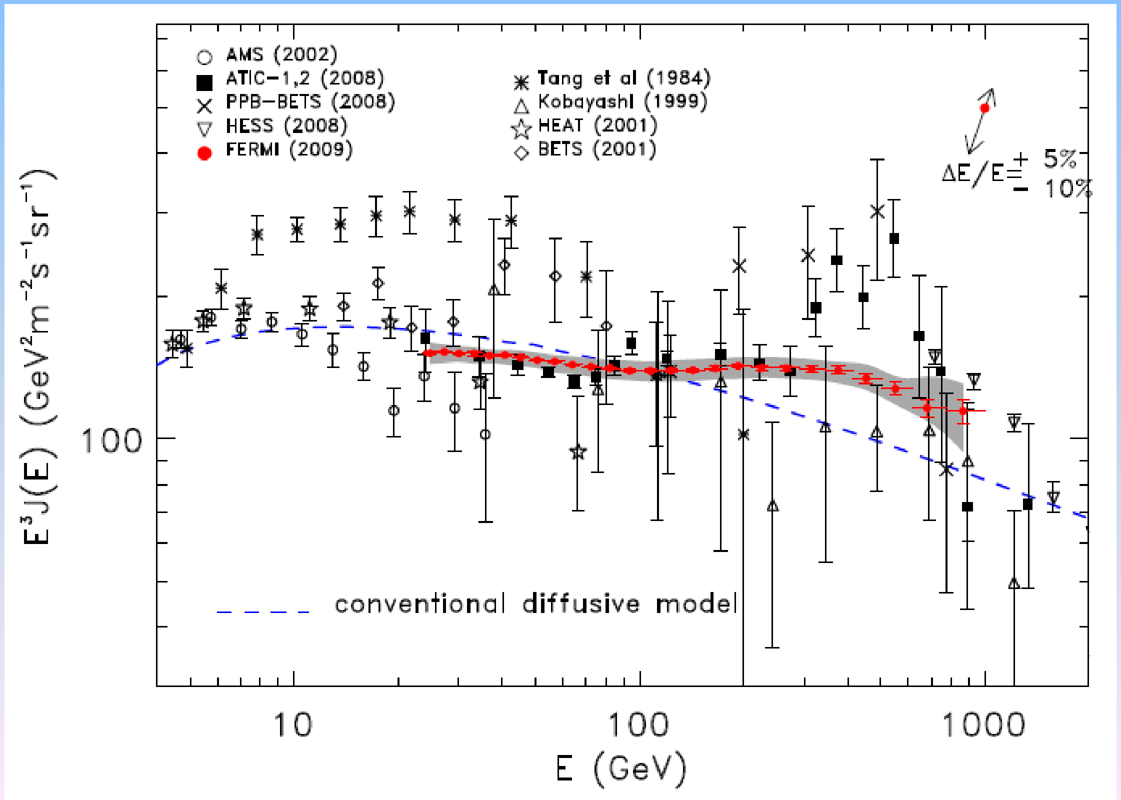



ATIC results showing agreement with previous data at lower … with the imaging calorimeter PPB-BETS at higher energy. The electron differential energy spectrum measured by ATIC (scaled by $E^3$) at the top of the atmosphere (red filled circles) is compared with previous observations from the Alpha Magnetic 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

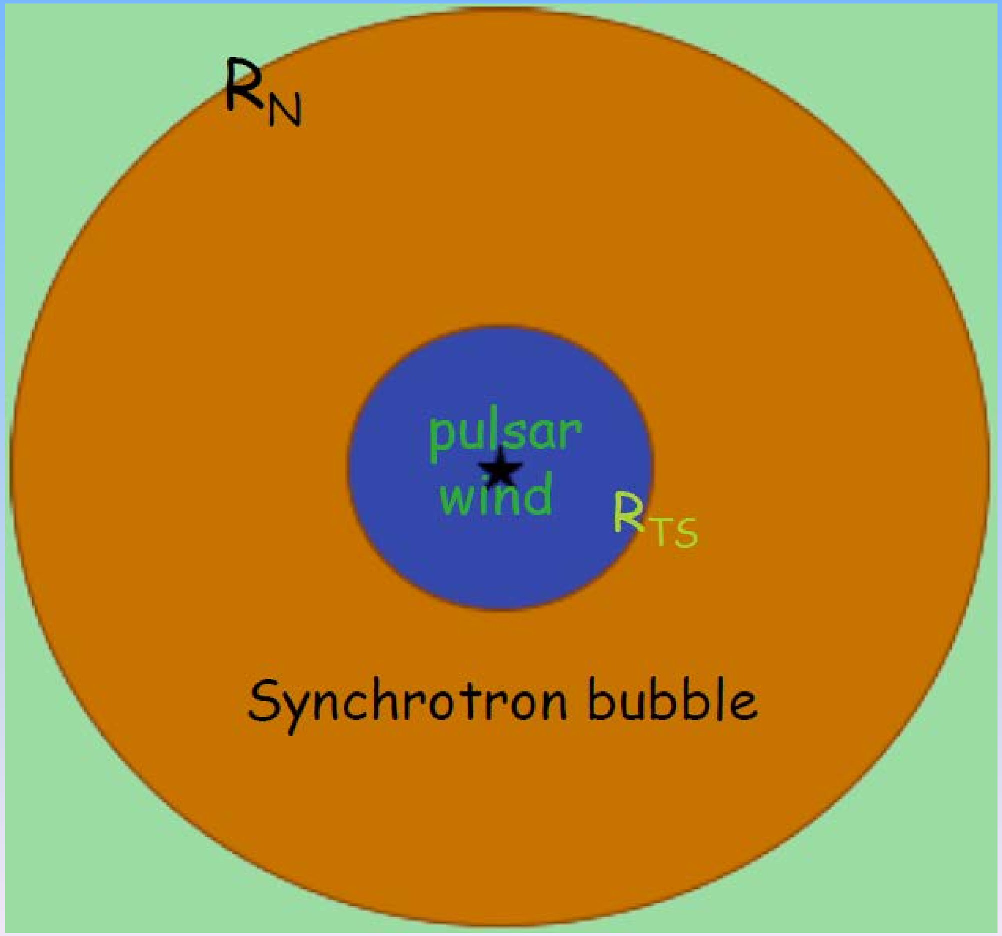


# 怎么理解实验观察到的超出呢？

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

# PWN as Electron and Positron Source

PWN (pulsar wind nebula)




$$\int_{E_{\min}}^{\infty} Q(E) E \, dE = \eta W_p \,,$$

$\eta$ is the efficiency of energy conversion

$$W_p = \dot{E} \, t \, (1 + t/\tau_0),$$

$\dot{E}$ and $t$ can be found in ATNF catalog

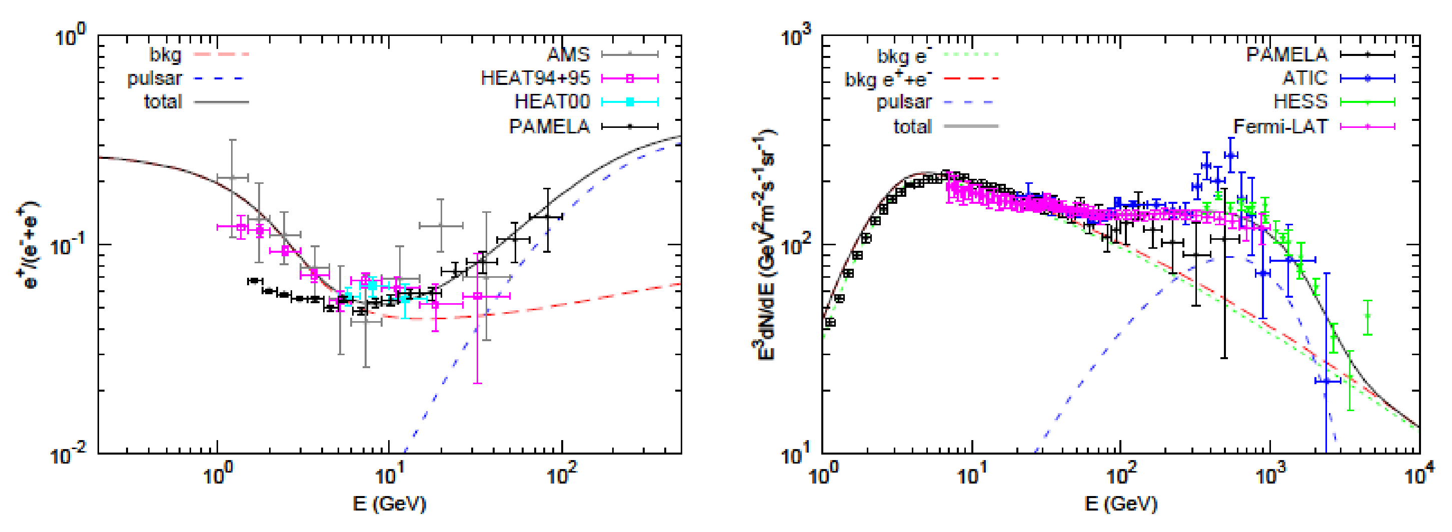



TABLE I. Fitting parameters with $1\sigma$ uncertainties or $2\sigma$ limits. Note that for the "bkg" case the reduced $\chi^2$ is too large that the uncertainties of the parameters should not be statistically meaningful.

| | bkg | bkg + pulsar | bkg + DM |
|---|---|---|---|
| $\gamma_1$ | <1.532 (95% C.L.) | <1.619 (95% C.L.) | <1.610 (95% C.L.) |
| $\gamma_2$ | $2.557 \pm 0.007$ | $2.712 \pm 0.014$ | $2.706 \pm 0.013$ |
| $\log(A_{bkg})$[a] | $-8.959 \pm 0.003$ | $-8.997 \pm 0.007$ | $-8.997 \pm 0.006$ |
| $E_{br}$ (GeV) | $3.599^{+0.123}_{-0.112}$ | $4.254^{+0.278}_{-0.287}$ | $4.283^{+0.246}_{-0.259}$ |
| $\phi$ (GV) | $0.324 \pm 0.016$ | $0.383 \pm 0.042$ | $0.371 \pm 0.037$ |
| $c_{e^+}$ | $1.462 \pm 0.035$ | $1.438^{+0.076}_{-0.079}$ | $1.394 \pm 0.053$ |
| $c_{\bar{p}}$ | $1.194 \pm 0.039$ | $1.225 \pm 0.043$ | $1.210 \pm 0.045$ |
| $\log(A_{psr})$[a] | – | $-27.923^{+0.534}_{-0.537}$ | – |
| $\alpha$ | – | $1.284 \pm 0.104$ | – |
| $E_c$ (TeV) | – | $0.861^{+0.170}_{-0.164}$ | – |
| $m_\chi$ (TeV) | – | – | $2.341^{+0.492}_{-0.391}$ |
| $\log[\sigma v(cm^3\,s^{-1})]$ | – | – | $-22.34 \pm 0.13$ |
| $B_e$ | – | – | <0.379 (95% C.L.) |
| $B_\mu$ | – | – | <0.334 (95% C.L.) |
| $B_\tau$ | – | – | $0.713^{+0.141}_{-0.152}$ |
| $B_u$ | – | – | <0.005 (95% C.L.) |
| $\chi^2$/d.o.f | 3.390 | 1.047 | 1.078 |

[a]In unit of $cm^{-2}\,sr^{-1}\,s^{-1}\,MeV^{-1}$.

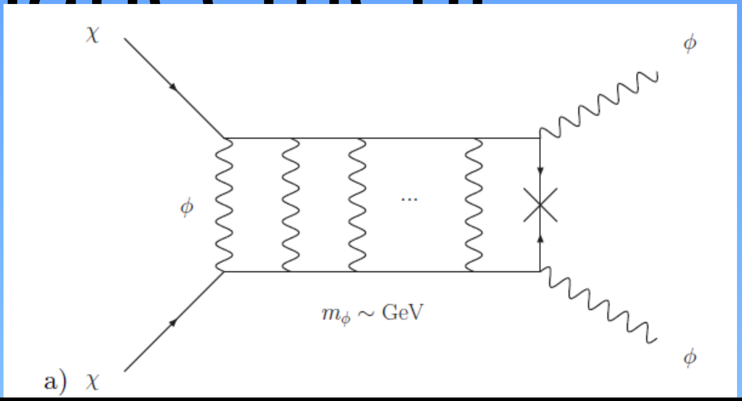
J.Liu, Q. Yuan, X-J Bi, H. Li, and X. Zhang, PRD85, 043507, 2012

DM can explain both the positron excesses and total spectrum; but it is not better than astrophysical explanation. To clarify the situation more precise data are necessary.

# 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

# Sommerfeld enhancement

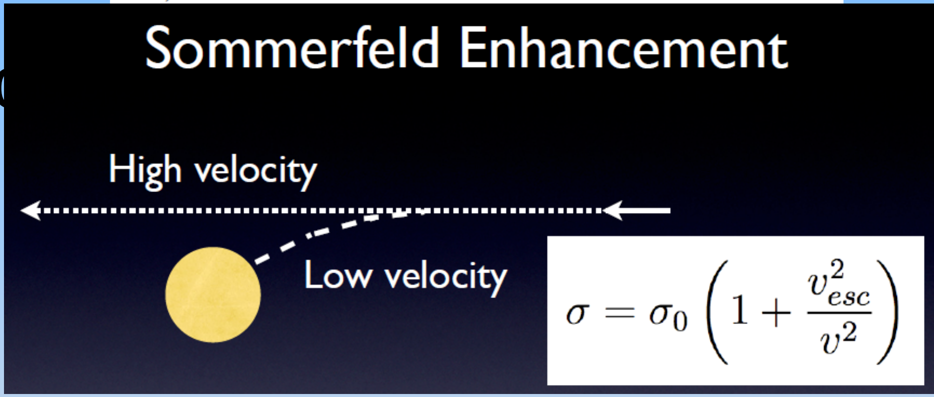



- Kinematically suppression

Mass of φis about 1GeV, is

Kinematically suppressed t

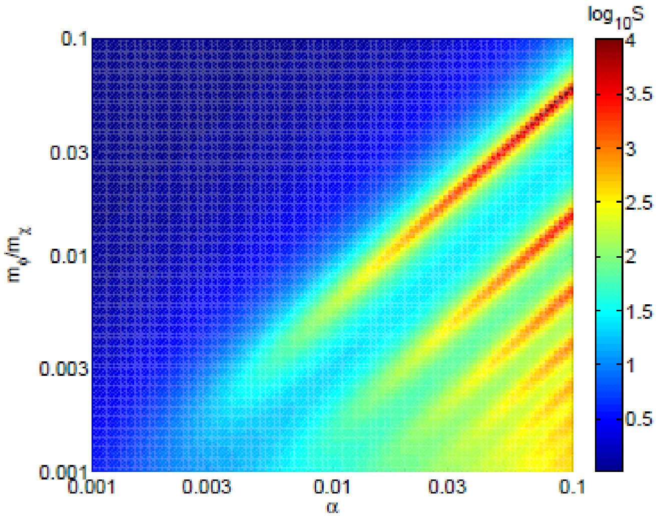
At the same time attractive enhance the annihilation enhancement. (Arkani-Hamed

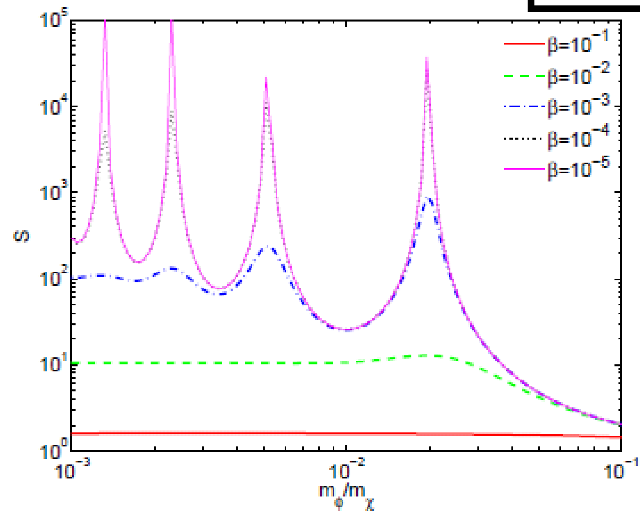


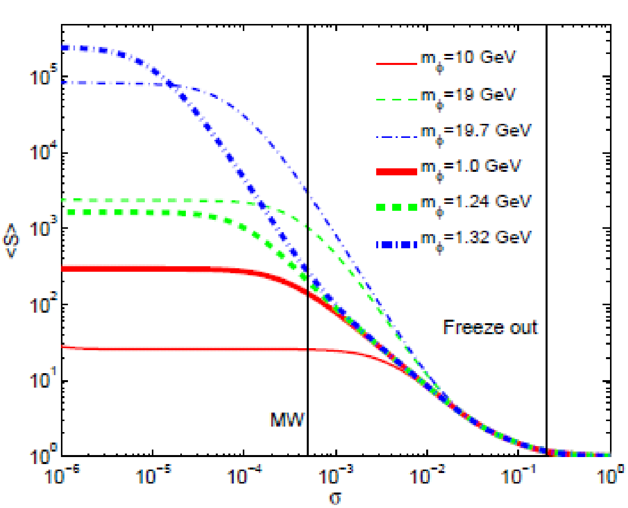

- For Coulomb potential we have
- $$S = \frac{|\psi_k(0)|^2}{|\psi_k^0(0)|^2} = \frac{2n\pi}{e^{2n\pi} - 1} = \frac{-\alpha\pi/v}{e^{-\alpha\pi/v} - 1}$$
- To enhance the dark matter annihilation we have long range attractive force $m_\phi^{-1} \gtrsim (\alpha M_{DM})^{-1}$

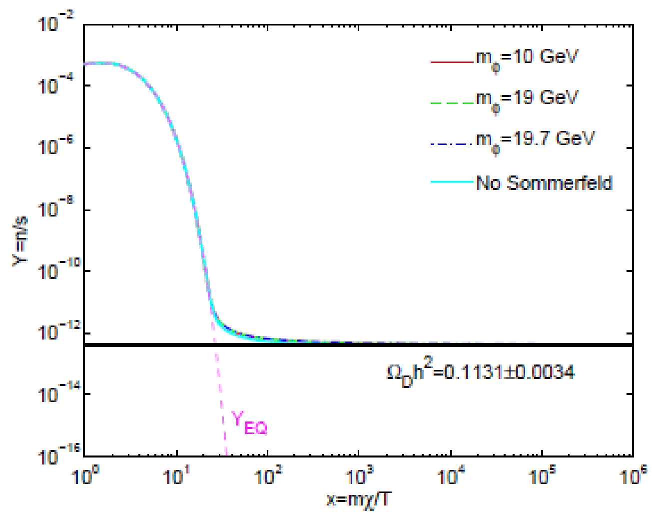
# Fine tunning of Sommerfeld enhancement

Yuan, Bi, Liu, Yin, Zhang and Zhu, Astro-ph/0905.2736



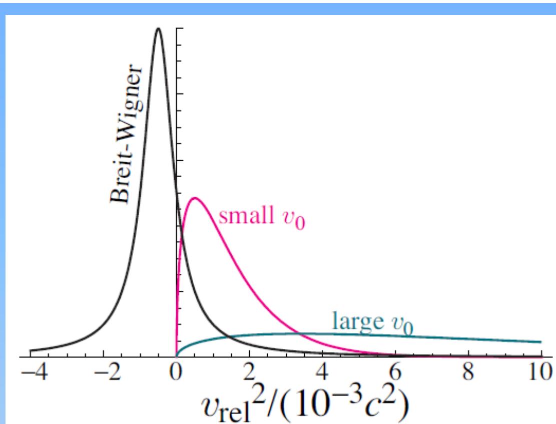



# Breit-Wigner enhancement and fine tunning

$$\sigma = \frac{16\pi}{E_{\rm cm}^2 \bar{\beta}_i \beta_i} \frac{M^2\Gamma^2}{(E_{\rm cm}^2 - M^2)^2 + M^2\Gamma^2} B_i B_f,$$

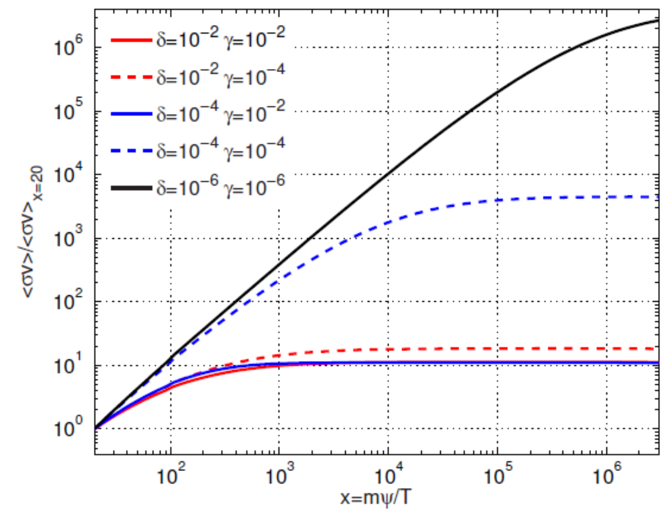
Bi, He, Yuan,

Astro-ph/0903.0122




Ibe, Murayama, Yanagida

Guo, Wu

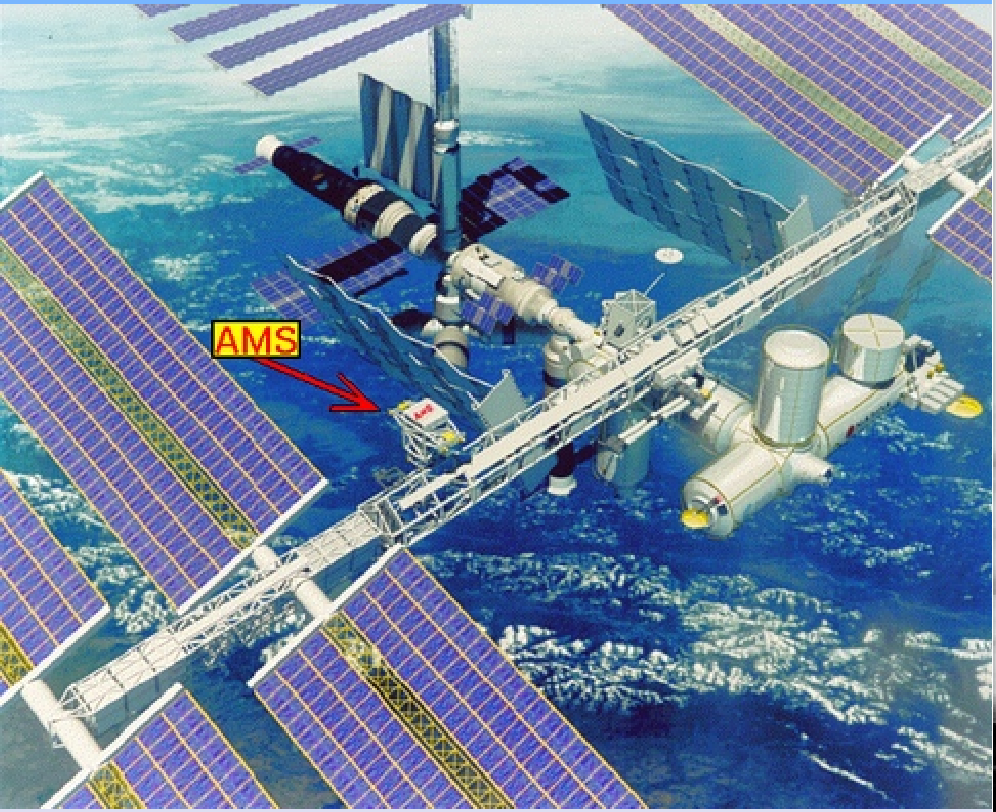



The Breit-Wigner enhanced relative cross section $\langle\sigma v\rangle/\langle\sigma v\rangle_{x=20}$ as a function of time $x$.

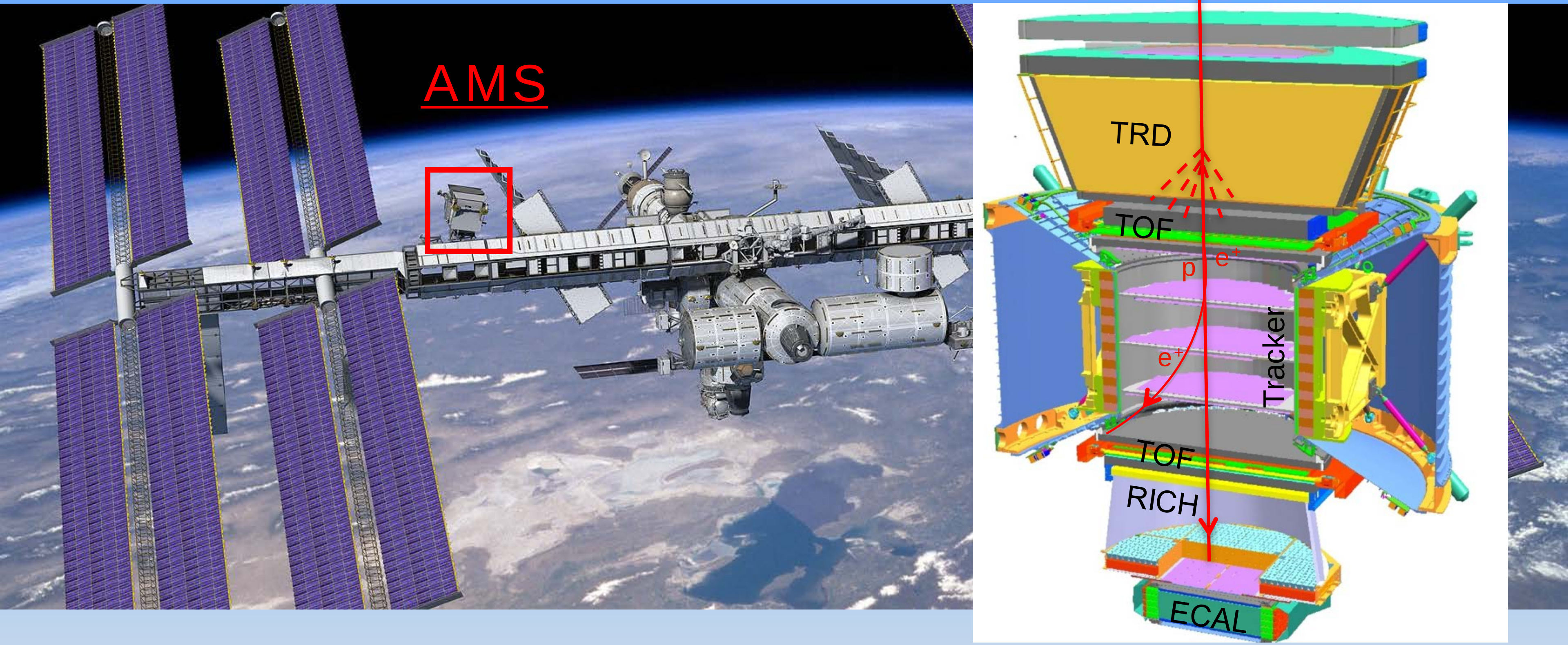
$$m_{Z'}^2 = 4m_\psi^2(1-\delta), \text{ and } \gamma^2 = \Gamma_{Z'}^2(1-\delta)/4m_\psi^2$$

**We require delta, gamma ~ $10^{-4}$ to boost ~1000.**

# AMS-02




# AMS02是国际空间站上唯一大型科学实验，将长期在轨运

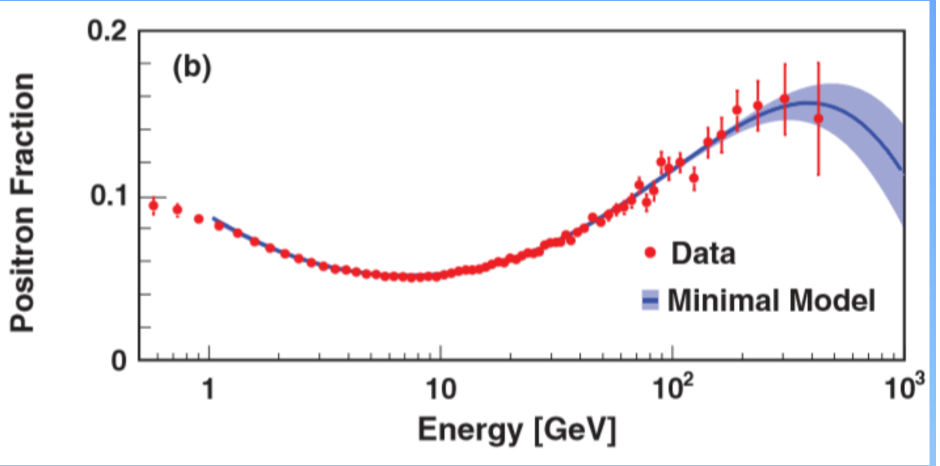


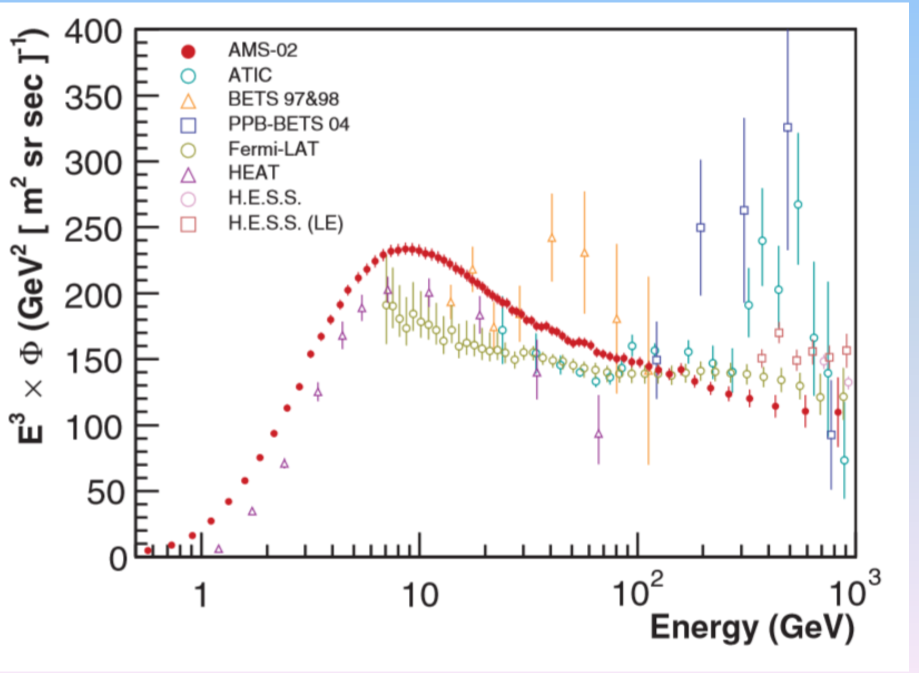

AMS物理目标：暗物质寻找

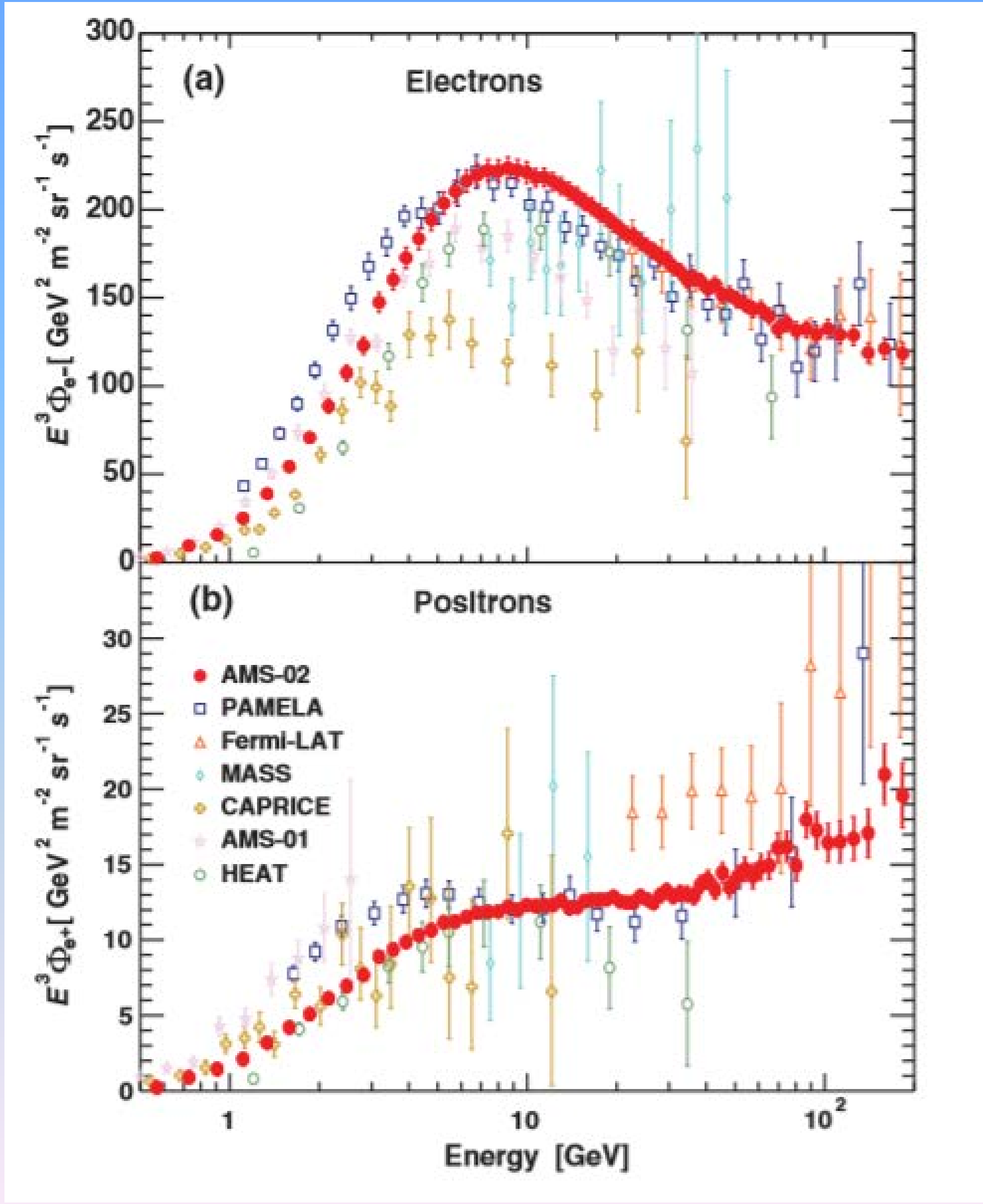
AMS物理目标：寻找反物质

AMS物理目标：带电宇宙线的精确测量

# Measurement of cosmic electron and positron spectra



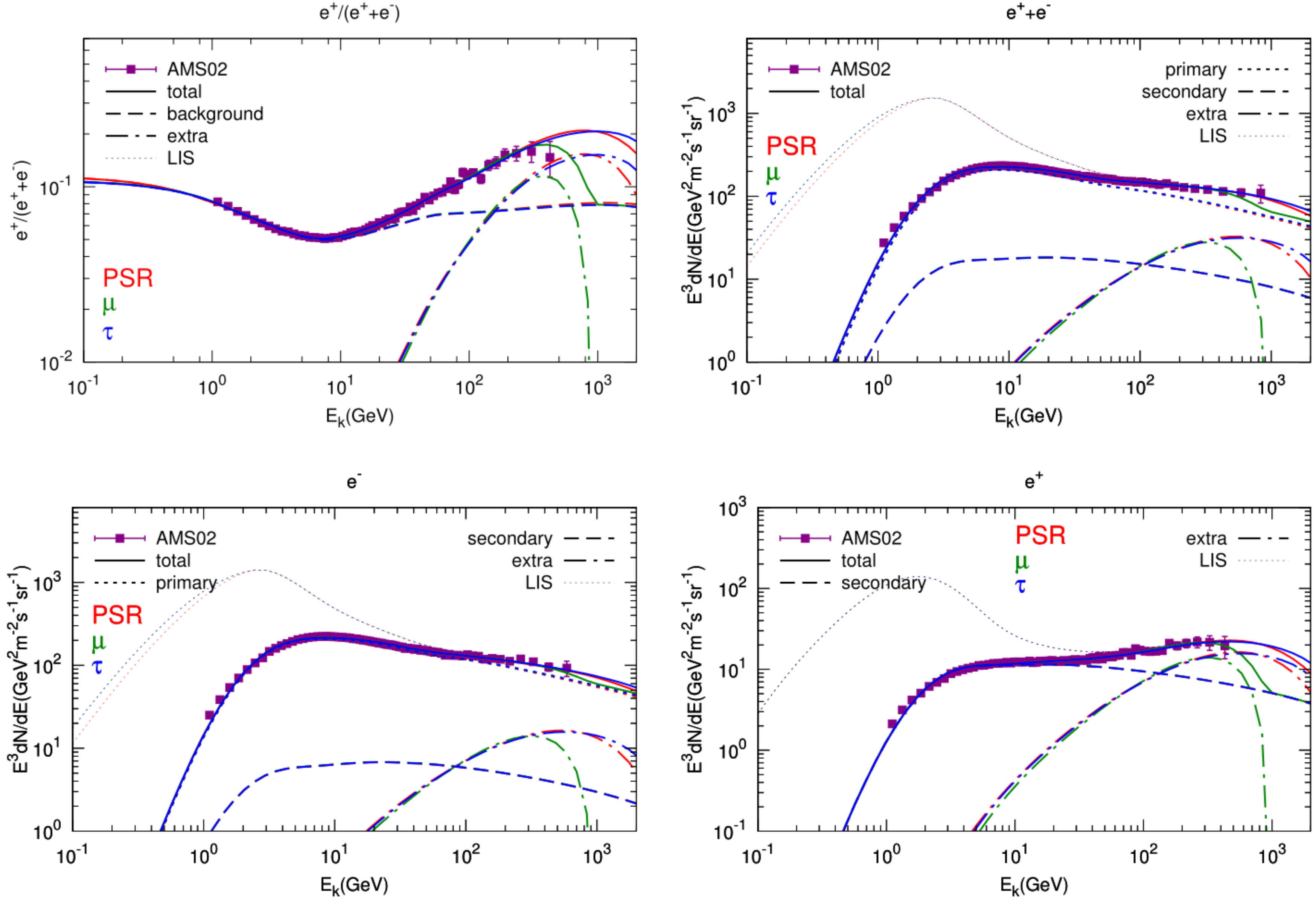



1409.6248

# Quantitative study of the AMS-02 electron/positron spectra: implications for the pulsar and dark matter properties

Su-Jie Lin, Qiang Yuan, and Xiao-Jun Bi
*Key Laboratory of Particle Astrophysics, Institute of High Energy Physics,*



# Conclusions of the quantitative study II

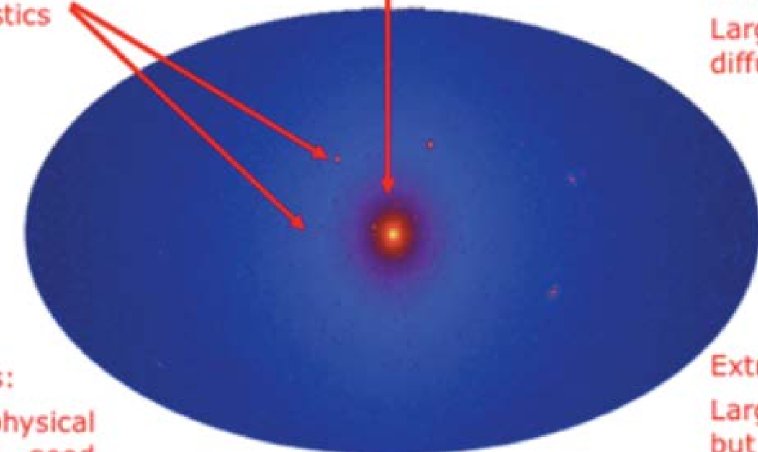
Both astrophysical sources, like pulsars, or dark matter can give good fit the AMS-02 data. AMS02 data can not distinguish the two scenarios.

| | | $\frac{\chi^2}{\text{d.o.f.}}$ | $\chi^2$ | $\frac{e^+}{e^+ + e^-}$ | $e^-$ | $e^+$ |
|---|---|---|---|---|---|---|
| | PSR | 0.92 | 175.4 | 42.95 | 54.22 | 78.26 |
| DR | $\mu$ | 0.89 | 171.6 | 39.94 | 55.36 | 76.26 |
| | $\tau$ | 0.91 | 175.2 | 42.72 | 55.21 | 77.24 |
| | PSR | 0.47 | 88.99 | 51.87 | 14.77 | 22.35 |
| DC | $\mu$ | 1.16 | 223.1 | 88.7 | 46.95 | 87.45 |
| | $\tau$ | 0.62 | 118.0 | 59.5 | 21.52 | 37.02 |

Satellites:
Low background and good source ID, but low statistics

Galactic center:
Good statistics but source confusion/diffuse background

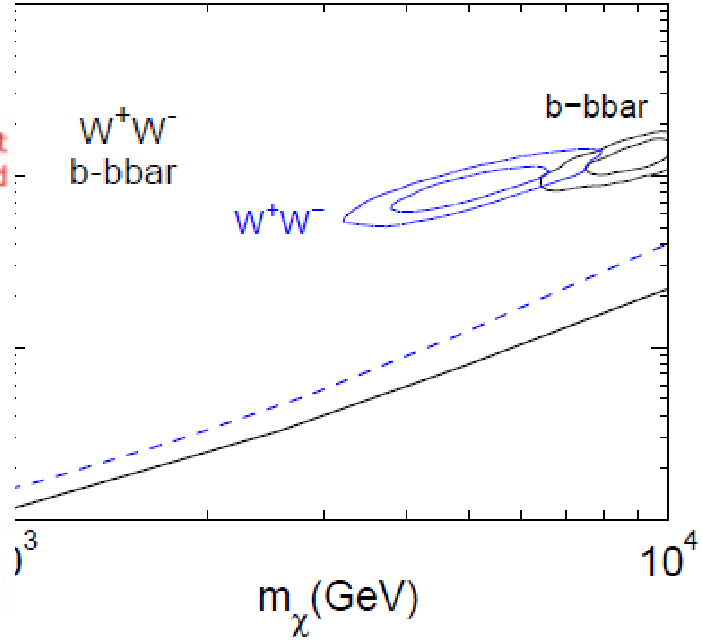
Milky Way halo:
Large statistics but diffuse background

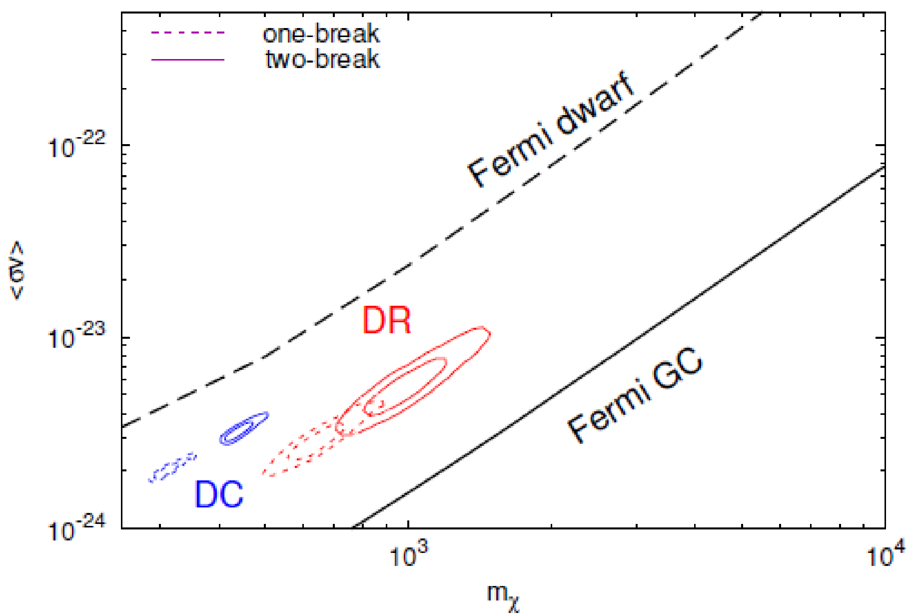


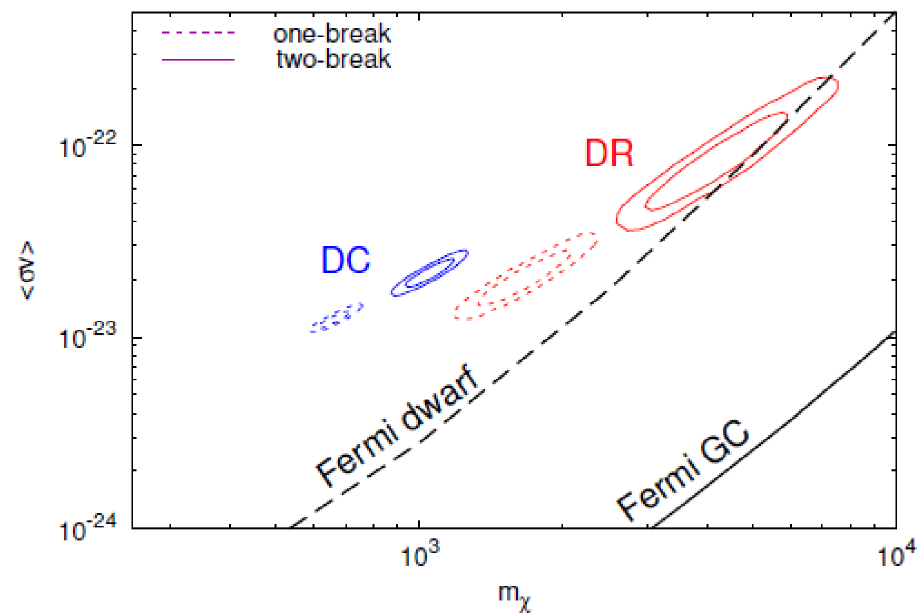
Spectral lines:
No astrophysical uncertainties, good source ID, but low statistics

Galaxy clusters:
Low background but low statistics

Extragalactic:
Large statistics, but astrophysics, Galactic diffuse background



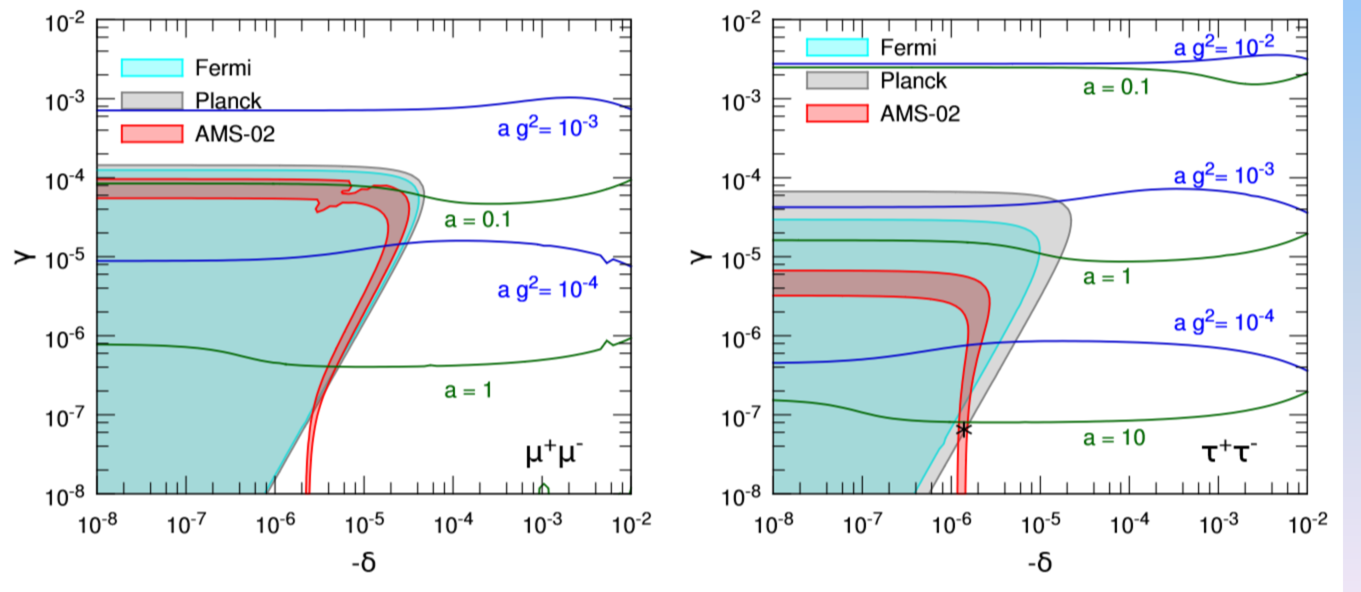



# Breit-weigner resonance

$$\mathscr{L}_{int} \supset -g(a\bar{\psi}\gamma^\mu\psi + \bar{l}_i\gamma^\mu l_i)Z'_\mu.$$

$$\sigma v = \frac{1}{6\pi}\frac{a^2 g^4 s}{(s-m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2}\left(1+\frac{2m_\psi^2}{s}\right),$$




(a)$\mu^+\mu^-$ channel.

(b)$\tau^+\tau^-$ channel.

**Simplest view of propagation**

$$G \propto \exp\left(-\frac{|\vec{x}_S - \vec{x}_\odot|^2}{\lambda_D^2}\right)$$

with $\lambda_D = \sqrt{4K_0\Delta\tilde{t}} = f(E_S, E_D)$

$\rightarrow$ Detection volume scaling a sphere of radius $\lambda_D$

Figures:

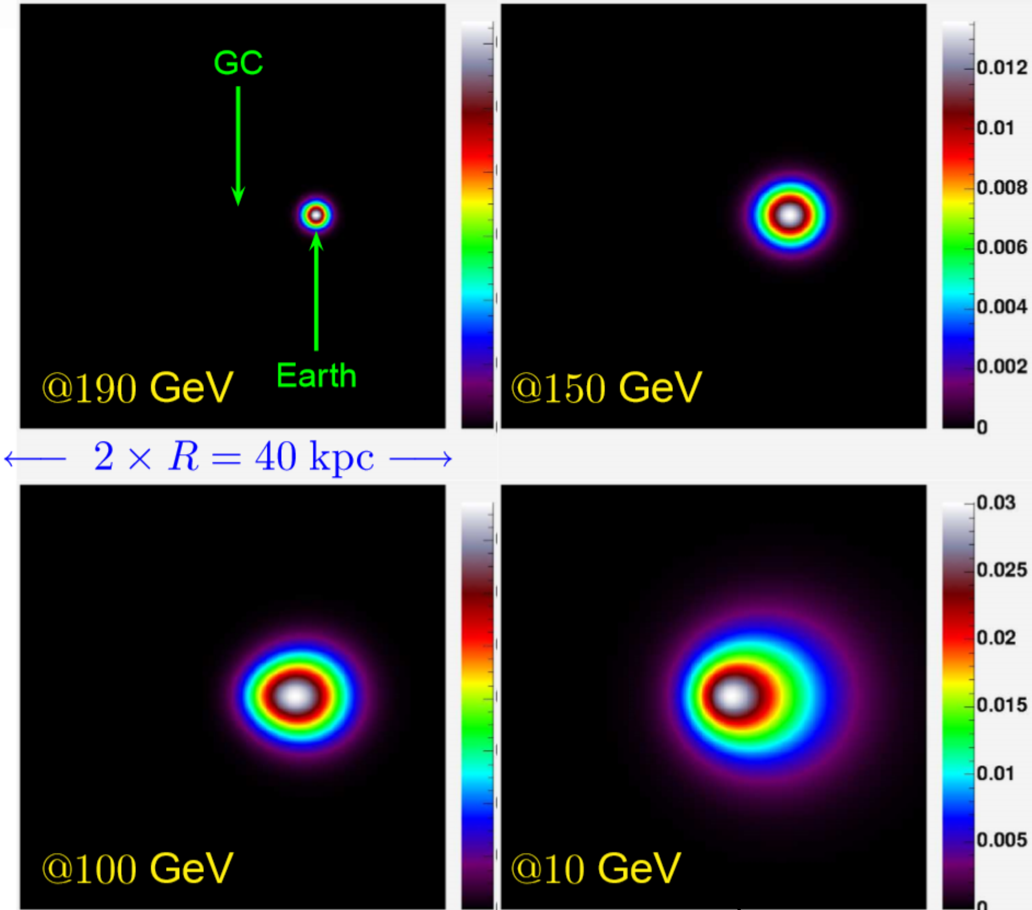
galactic plane at z=0 kpc

$x$ and $y$ from -20 to 20 kpc

Earth located at $(x = 8, y = 0)$ kpc

2D plots of

$G(\vec{x}, 200\mathrm{GeV} \rightarrow \tilde{x}_\odot, \mathrm{E}) \times \rho^2$



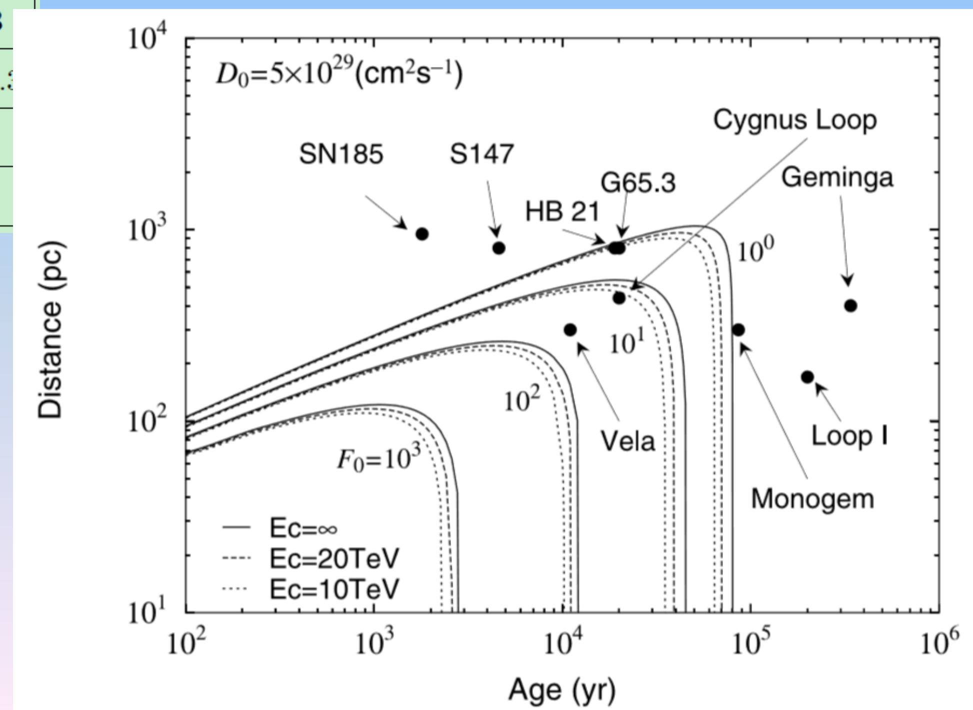

高能只能来自邻近，
具有方向性

不同源的性质不同，可能
高能电子贡献能谱的结构

# Parameters of SNRs

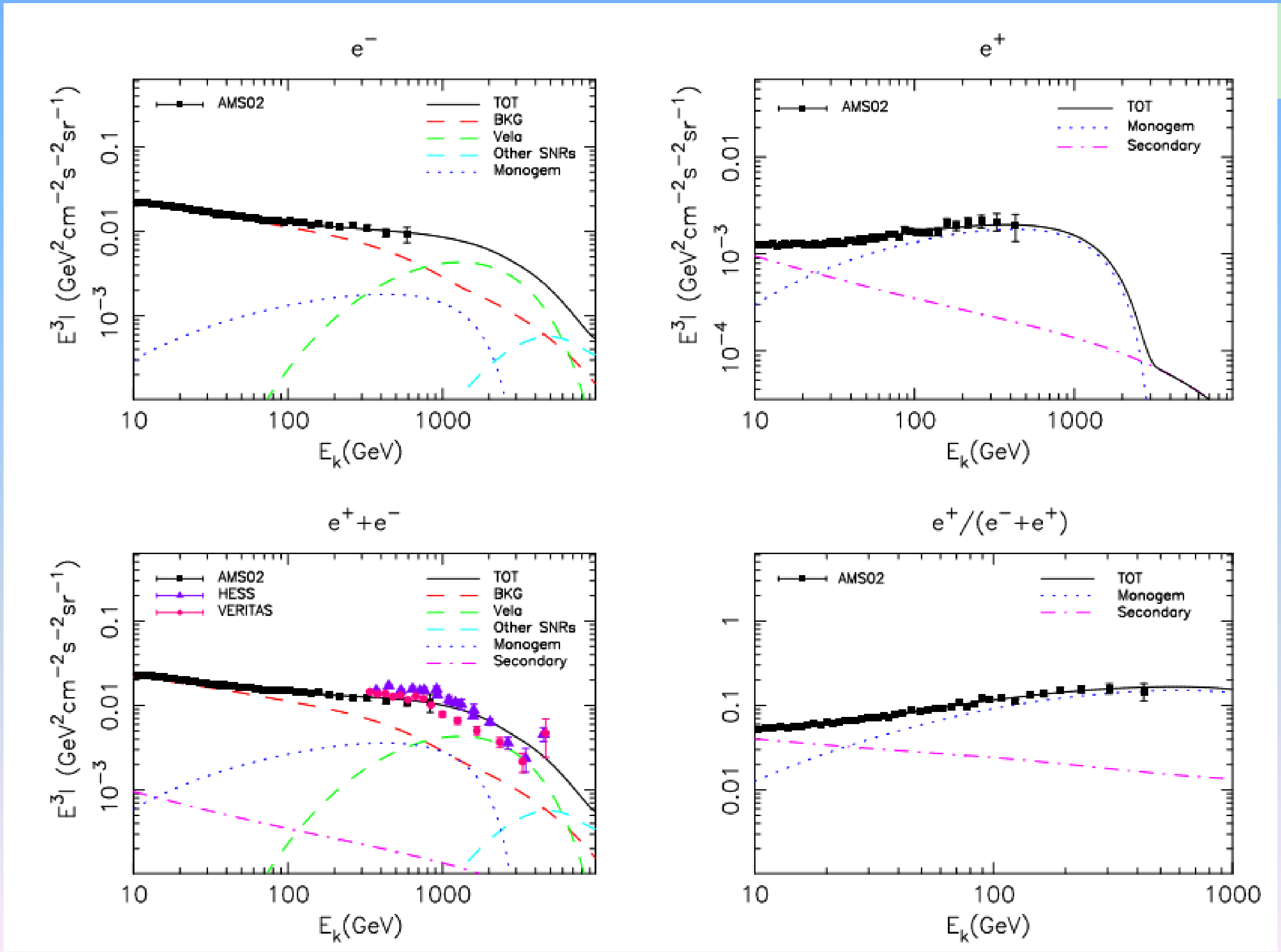
| Source | Other Name | $B_r^{1\mathrm{GHz}}$[Jy] | $\alpha_r$ | Size[arcmin] | r[kpc] | t[kyr] |
|---|---|---|---|---|---|---|
| G065.3+05.7 | - | 52 | 0.58 | $310 \times 240$ | 0.9 | 26 |
| G074.0–08.5 | Cygnus Loop | 175 | 0.4 | $230 \times 160$ | 0.54 | 10 |
| G114.3+00.3 | - | 6.4 | 0.49 | $90 \times 55$ | 0.7 | 7.7 |
| G127.1+00.5 | R5 | 12 | 0.43 | 45 | 1 | [20, 30] |
| G156.2+05.7 | - | 5 | 0.53 | 110 | 1.0 | [15, 26] |
| G160.9+02.6 | HB9 | 88 | 0.59 | $140 \times 120$ | 0.8 | [4, 7] |
| G203.0+12.0 | Monogem Ring | - | - | - | 0.3 | 86 |
| G263.9–03.3 | Vela YZ | varies | varies | 255 | 0.29 | 11.3 |
| G266.2–01.2 | Vela Jr. | 50 | 0.3 | 120 | 0.75 | [1.7, 4.3 |
| G328.3+17.6 | Loop I (NPS) | - | - | - | 0.1 | 200 |
| G347.3–00.5 | RXJ1713.7-3946 | 4 | 0.3 | $65 \times 55$ | 1 | 1.6 |

Flux at 3TeV



# FITTING TO AMS-02

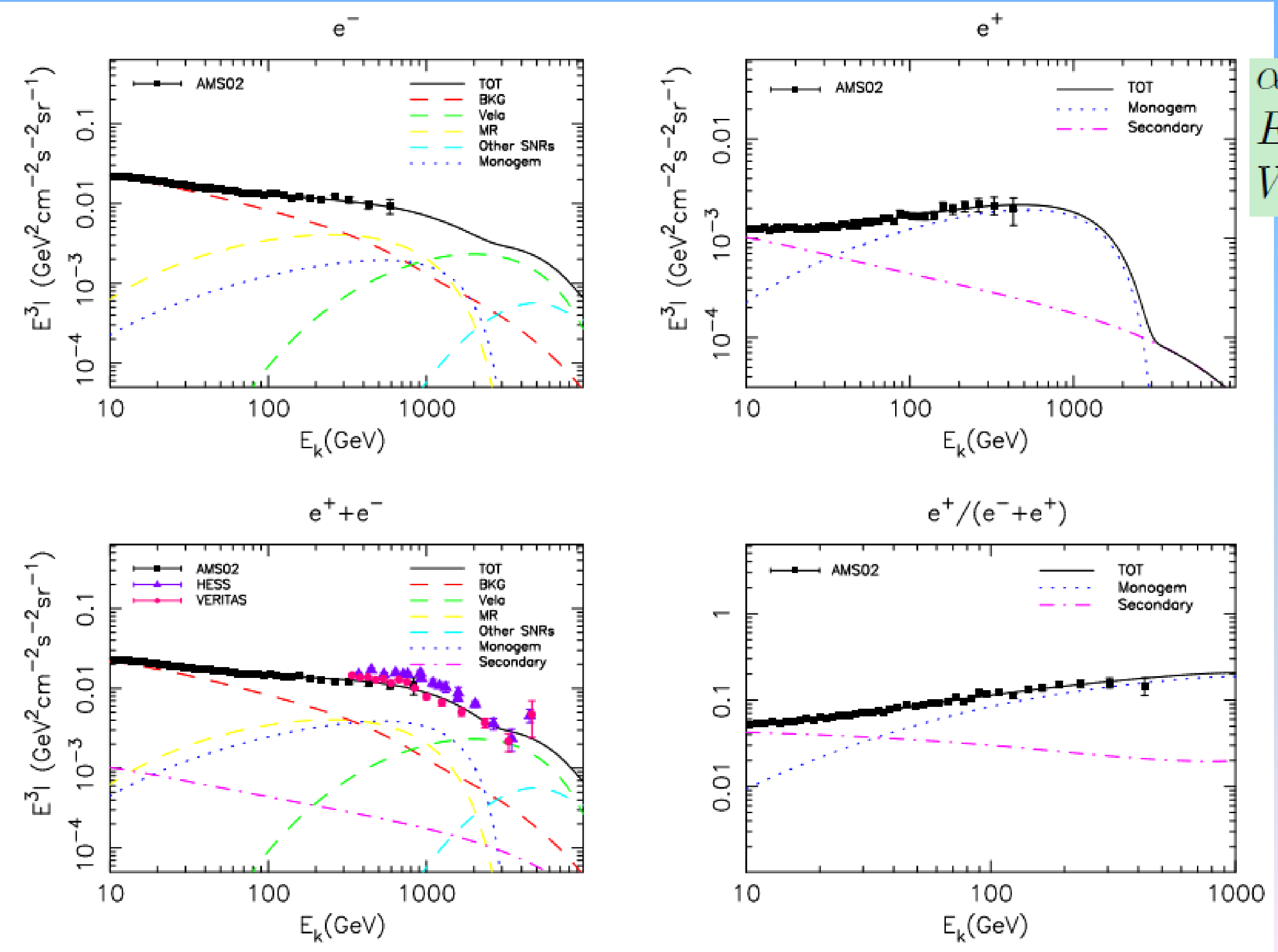
*Vela YZ* model




$\alpha_{vela} = 0.519$

# FITTING TO AMS-02

## *Vela YZ* + *Monogem Ring* model (α=0.53)



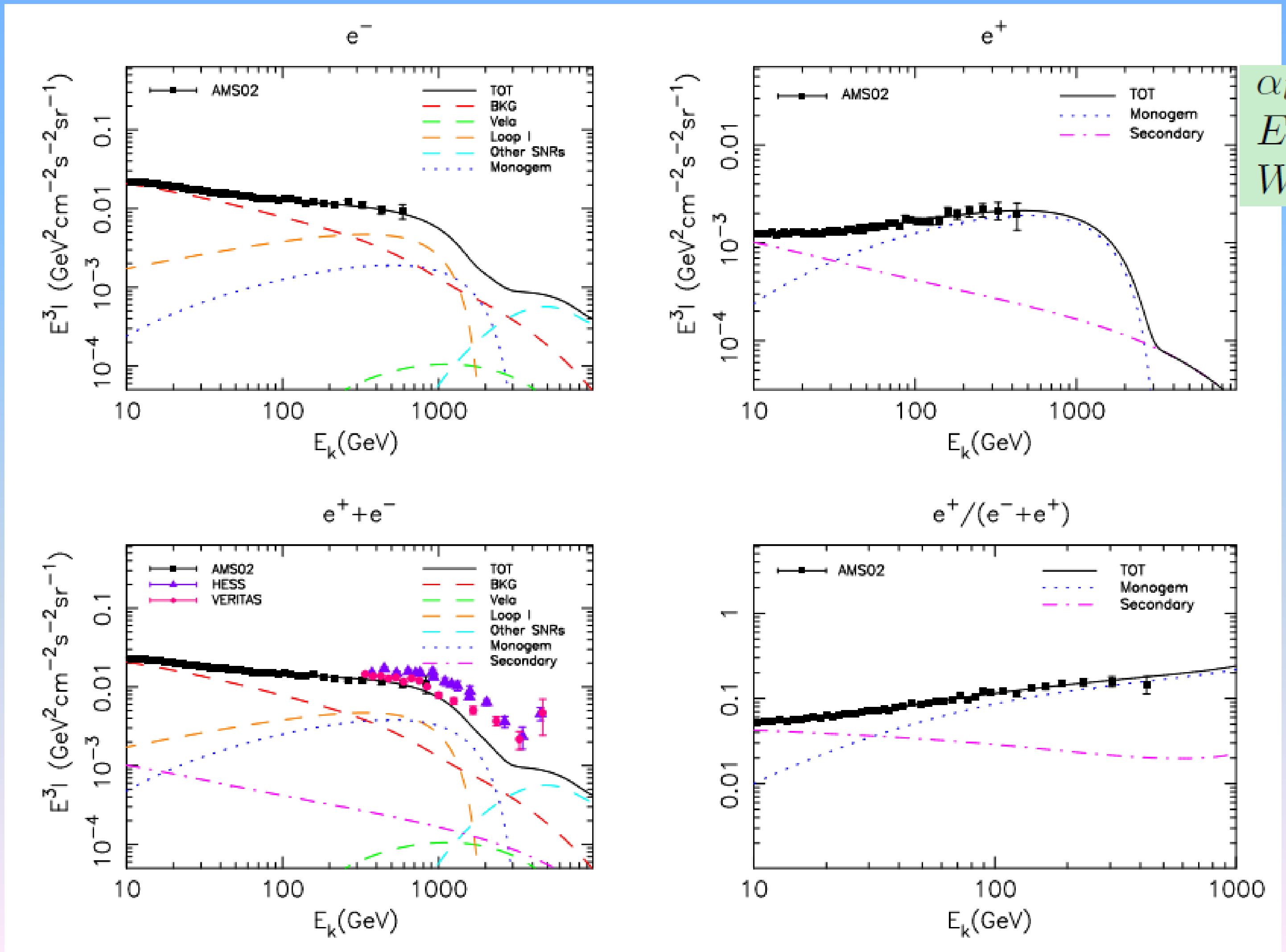

$\alpha_{mr} = 0.551$

$E_{c,mr} = 1.04$ TeV

$W_{mr} = 2.89 \times 10^{48}$ erg

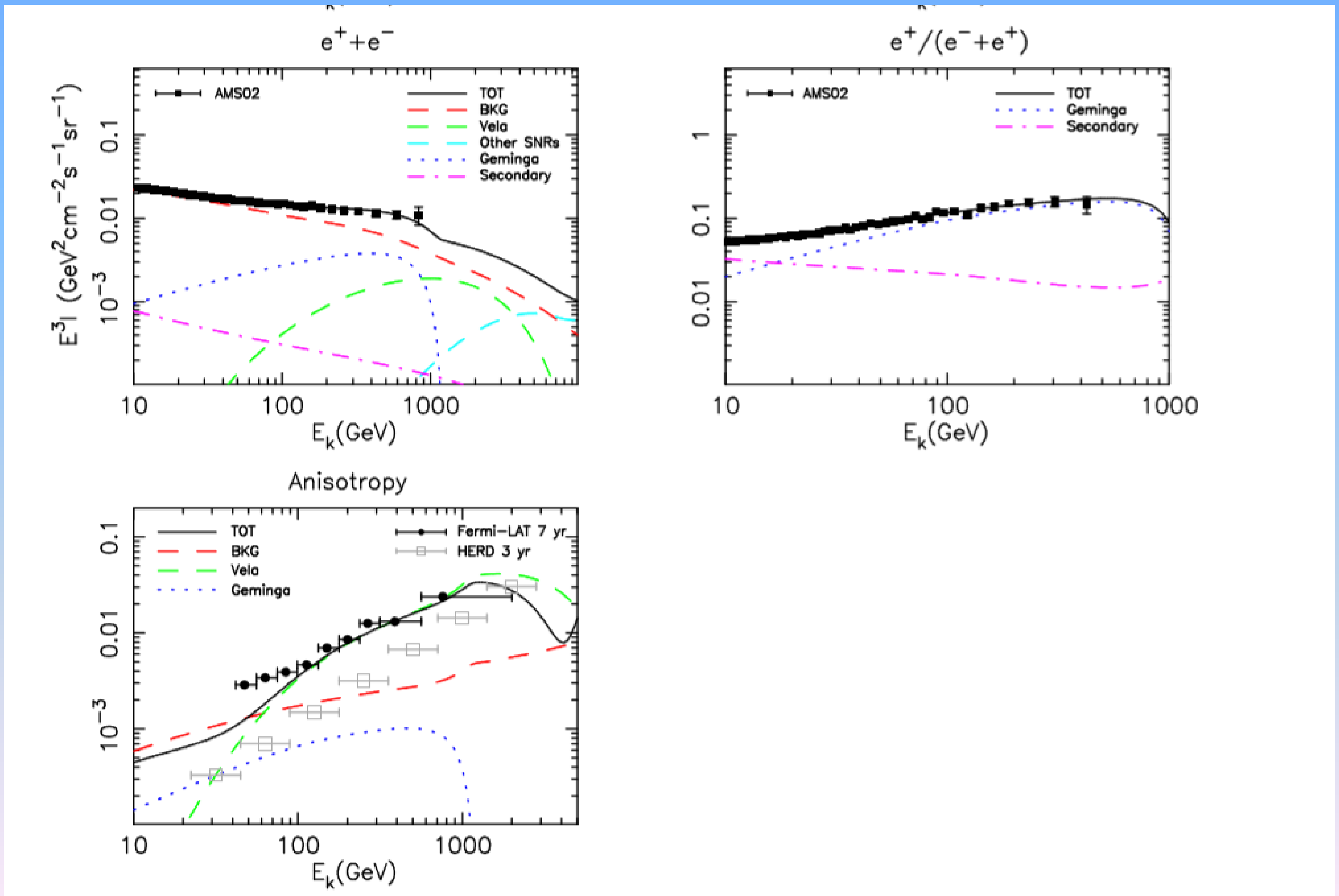
# FITTING TO AMS-02

*Vela YZ + Loop I* model (α=0.735)

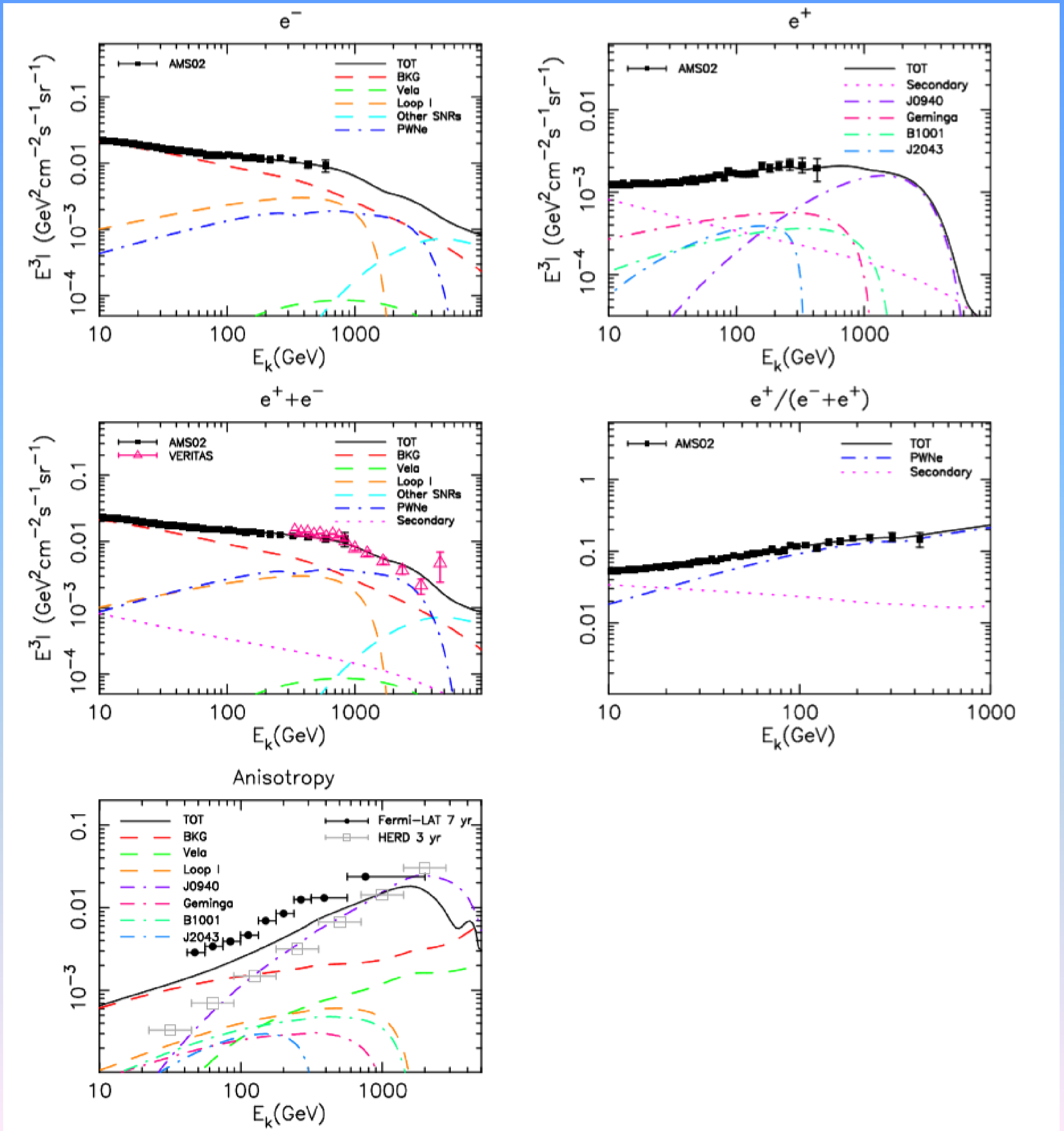



$$\alpha_{loop} = 0.417$$
$$E_{c,loop} = 1.49 \text{ TeV}$$
$$W_{loop} = 5.08 \times 10^{48} \text{ erg}$$

# Strong constraints on the vela XY contribution to AMS-02 lepton data

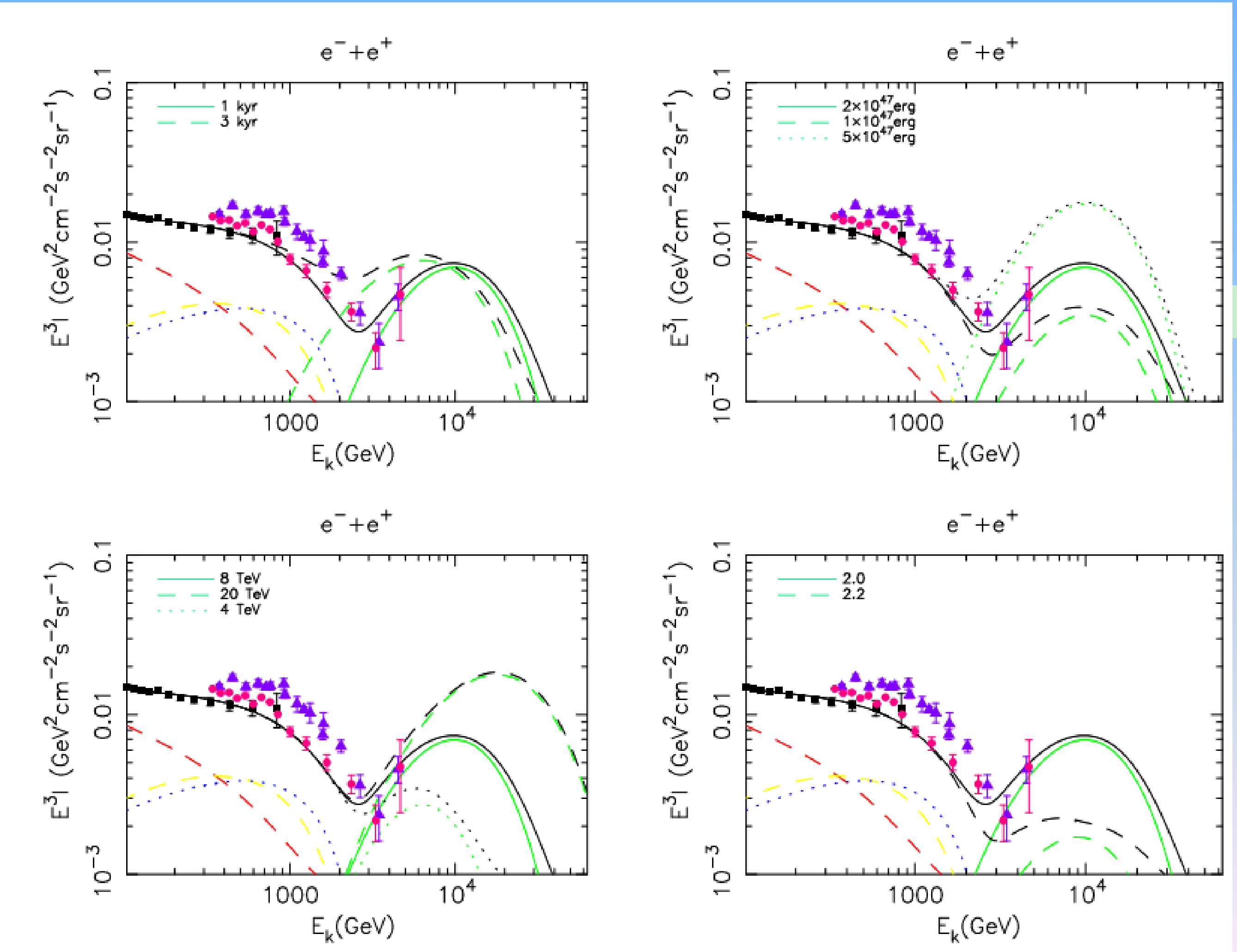


Fitting to present data implies constraint from HERD



# Predictions above TeV

## Vela YZ




top left:

$t = 1,\ 3$ kyr

top right:

$W = (1,\ 2,\ 5) \times 10^{47}$ erg

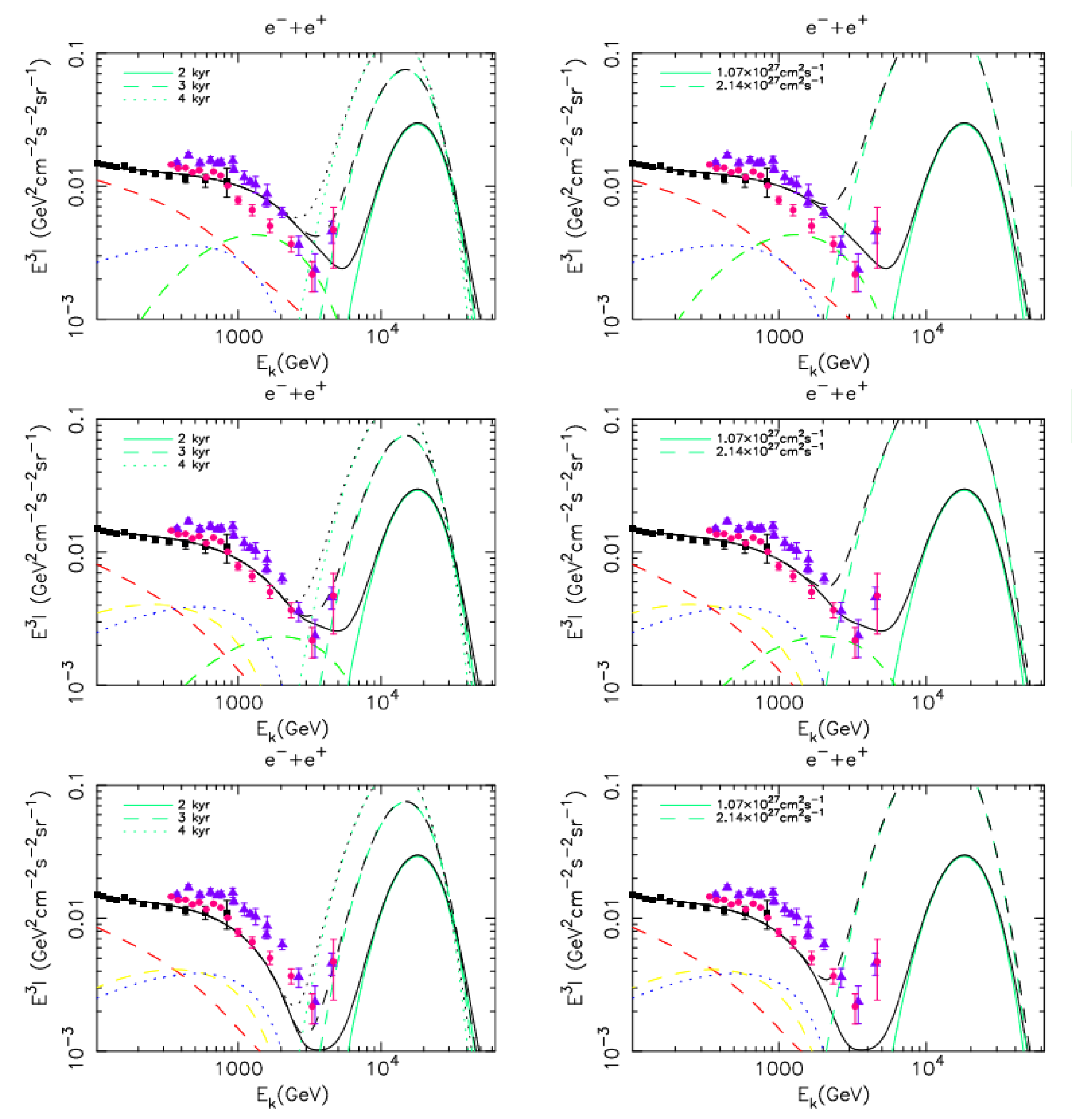
bottom left:

$E_c = 4,\ 8,\ 20$ TeV

bottom right:

$\gamma = 2.0,\ 2.2$

# Predictions above TeV from Vela X



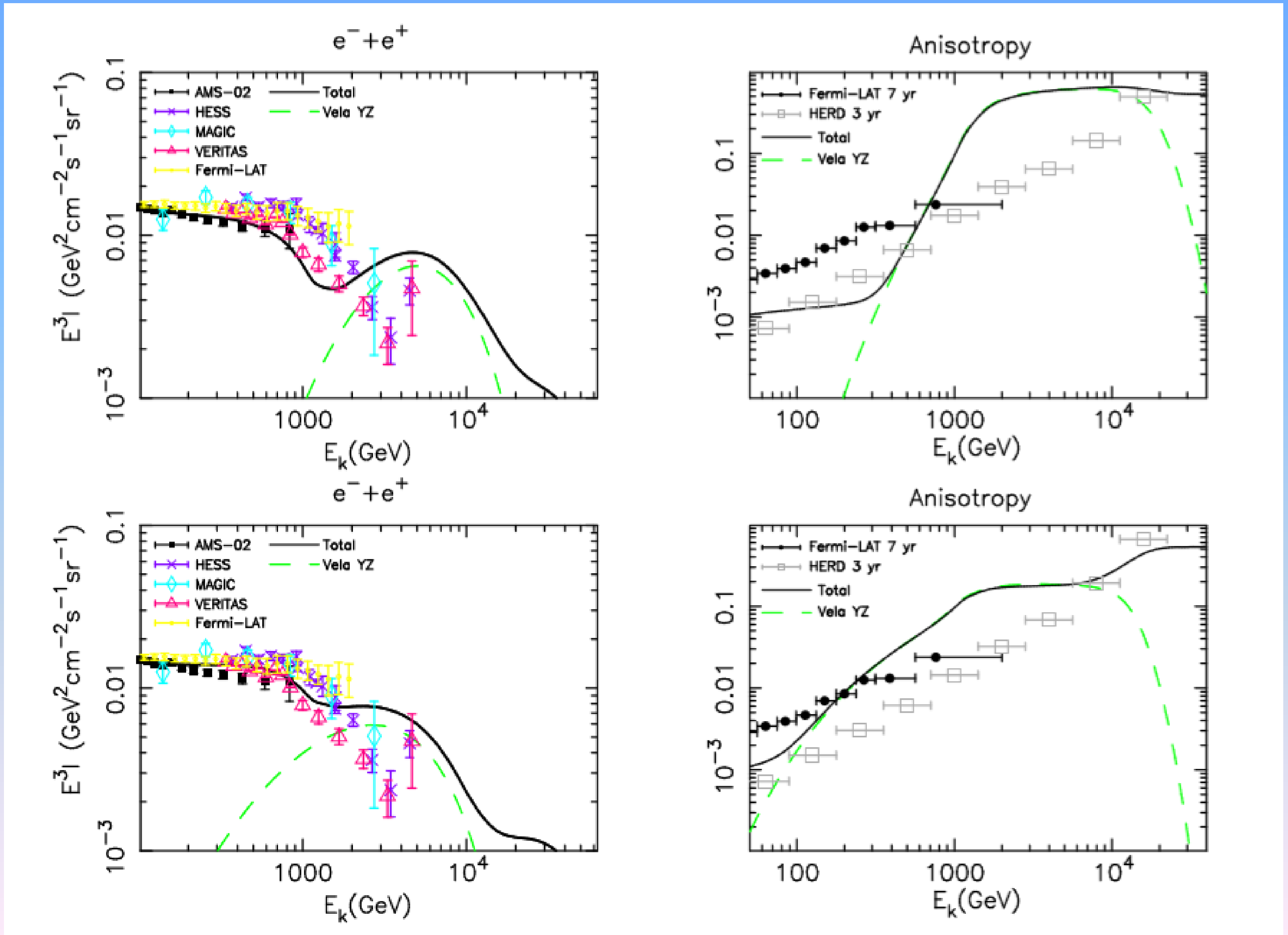

left:

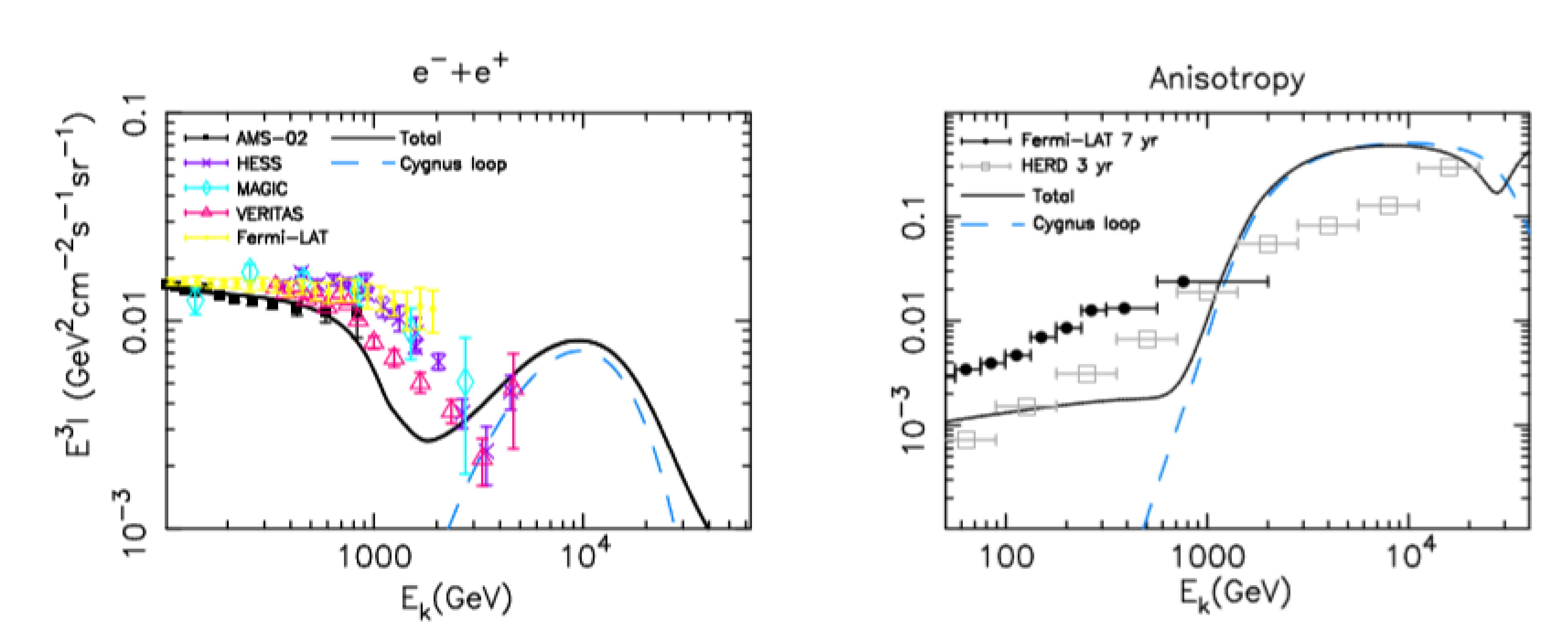
$t = 2,\ 3,\ 4\ \text{kyr}$

right:

$D_0 = (1.07, 2.14) \times 10^{27}\ \text{cm}^2\ \text{s}^{-1}$

# High energy bump and anisotropy constraint by Fermi and HERD

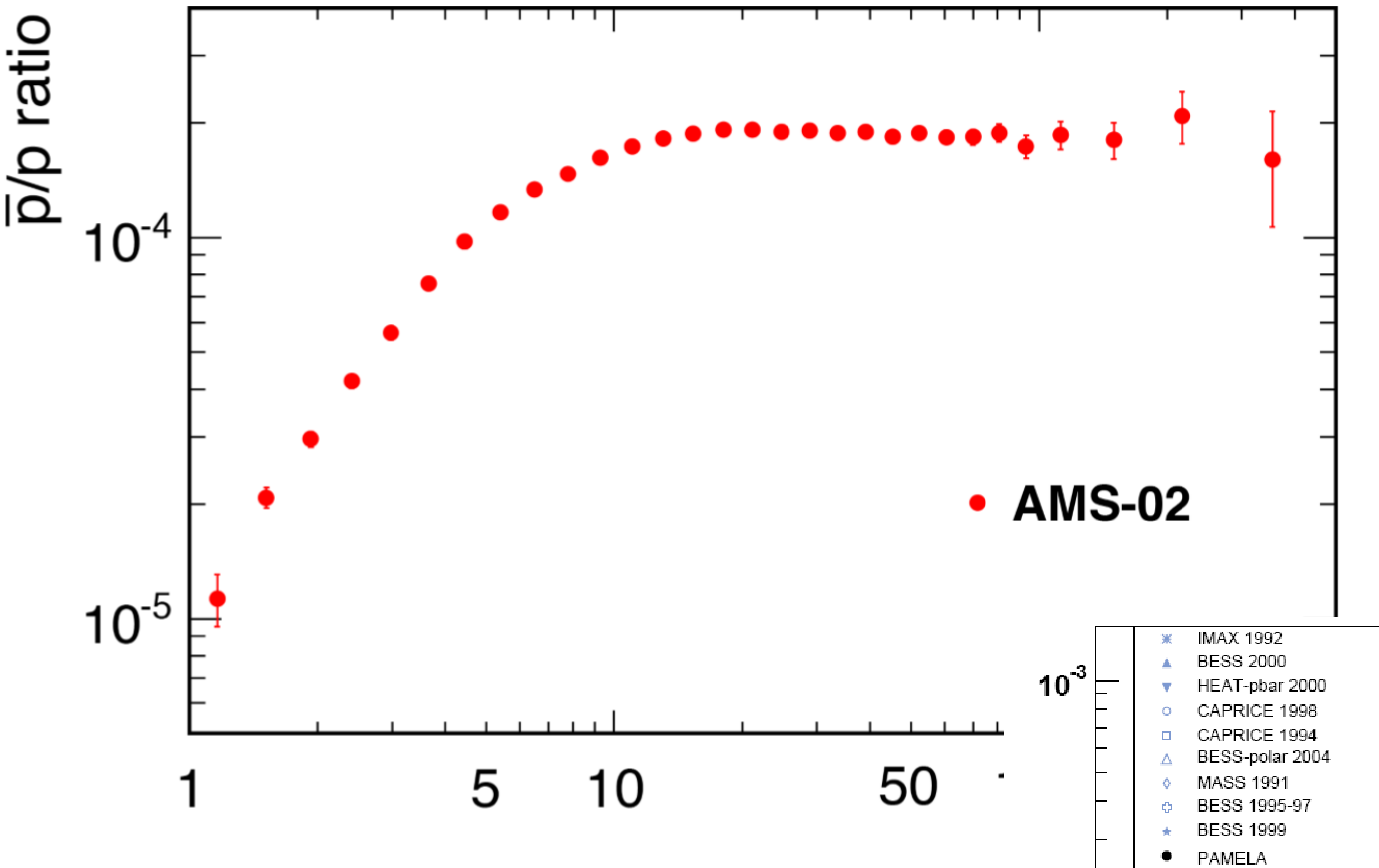




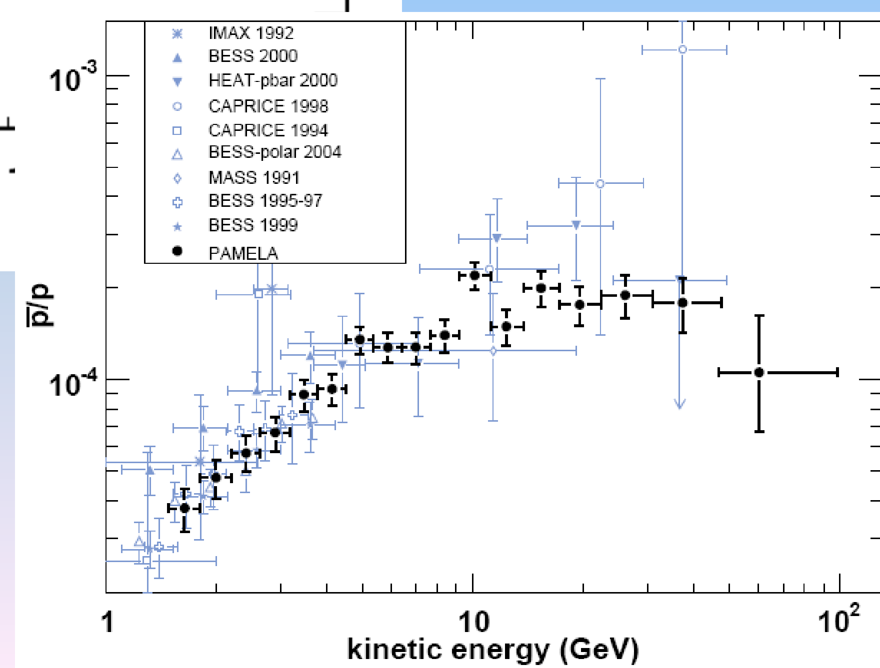
e⁻+e⁺
AMS-02
HESS
MAGIC
VERITAS
Fermi-LAT
Total
Cygnus loop
$E^3 I$ (GeV$^2$cm$^{-2}$s$^{-1}$sr$^{-1}$)
0.1
0.01
$10^{-3}$
1000
$10^4$
$E_k$(GeV)
Anisotropy
Fermi-LAT 7 yr
HERD 3 yr
Total
Cygnus loop
0.1
0.01
$10^{-3}$
100
1000
$10^4$
$E_k$(GeV)

# AMS $\bar{p}/p$ results

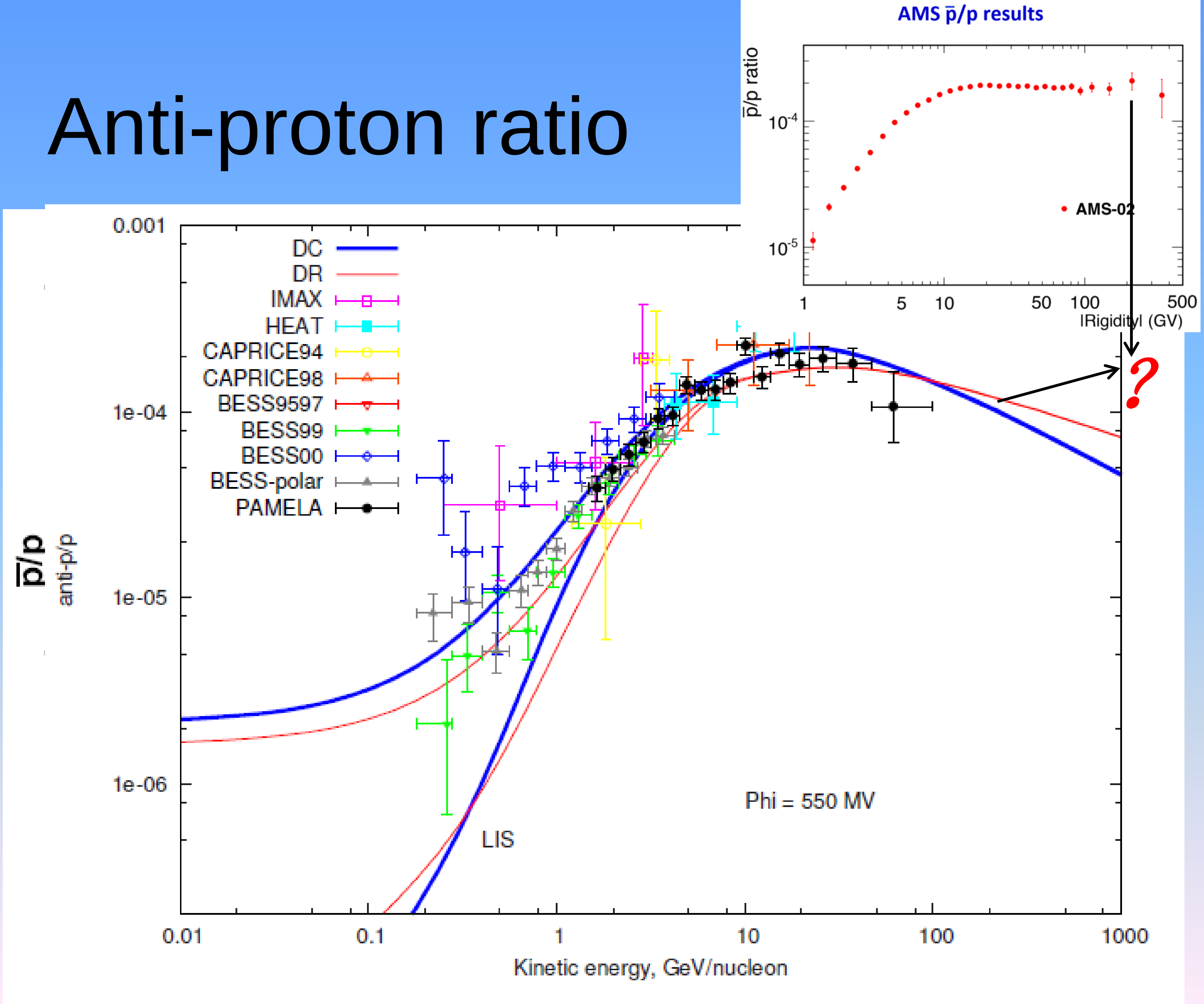
AMS-02 pbar/p



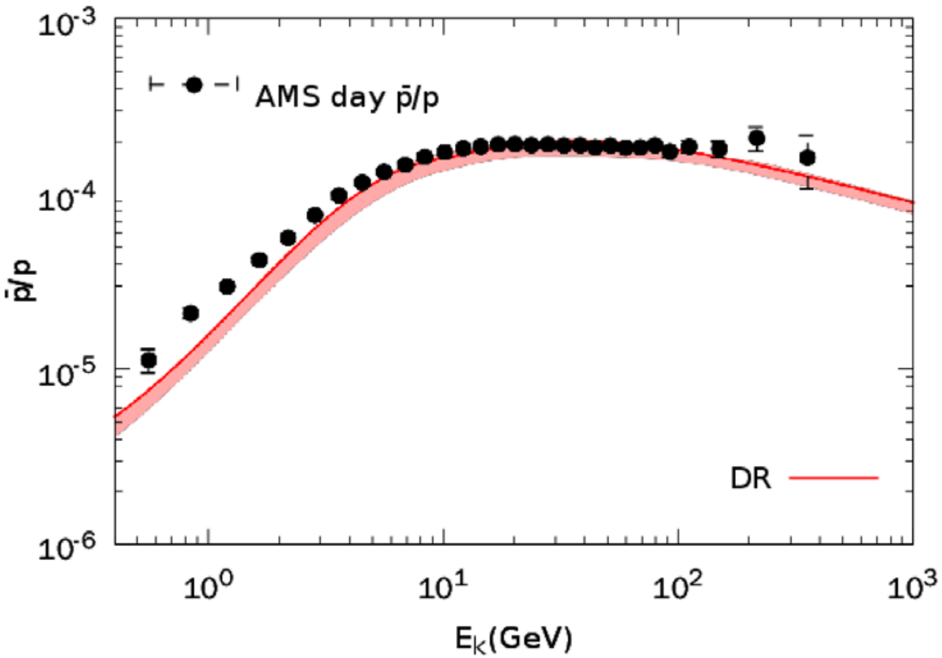

PAMELA pbar/p

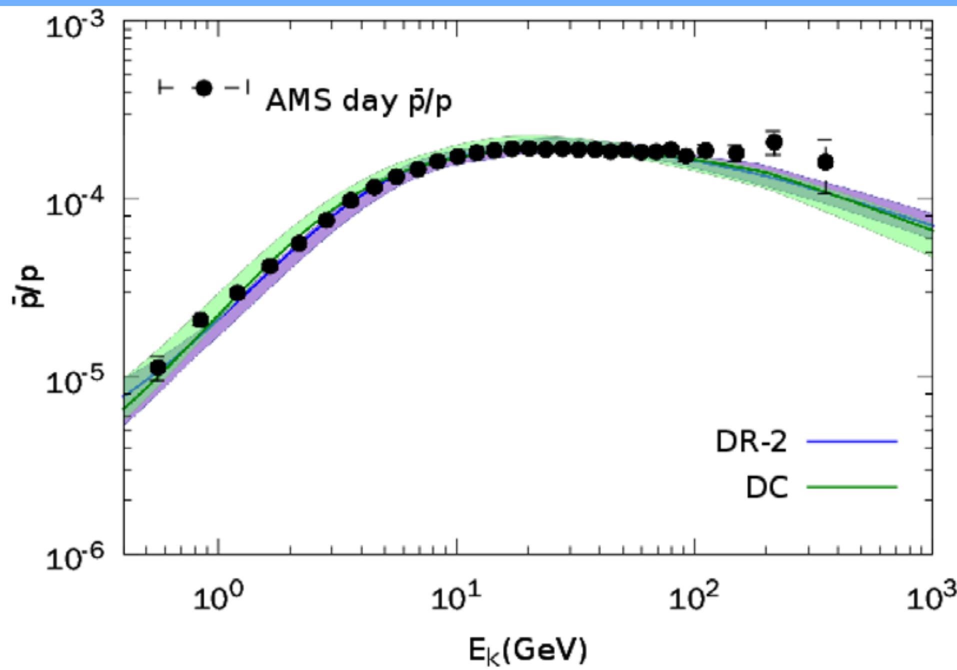


# Anti-proton ratio



# AMS-02 pbar/p

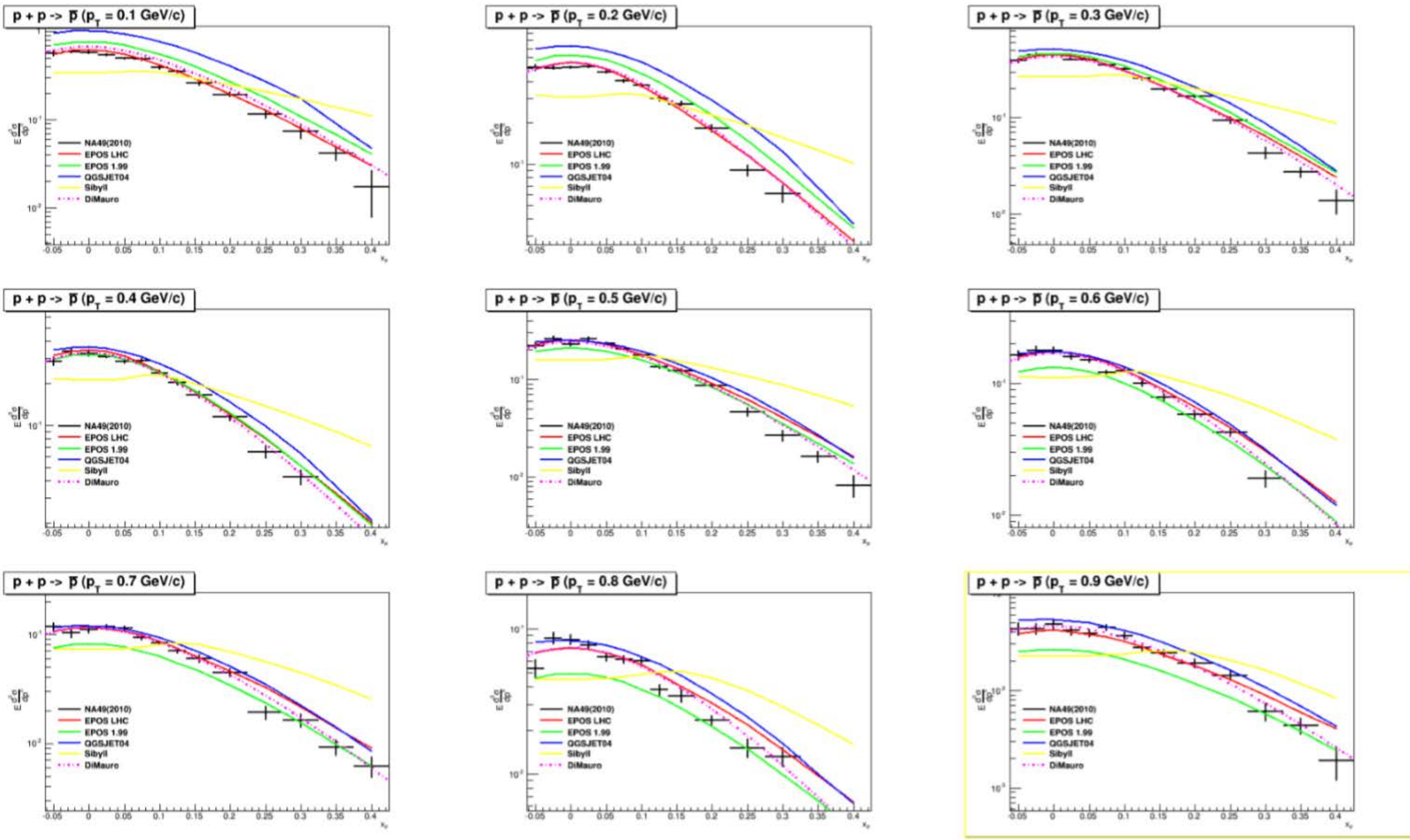



Calculation seems predict some excess at high energies. However, the prediction is based on an old hadronic interaction model.

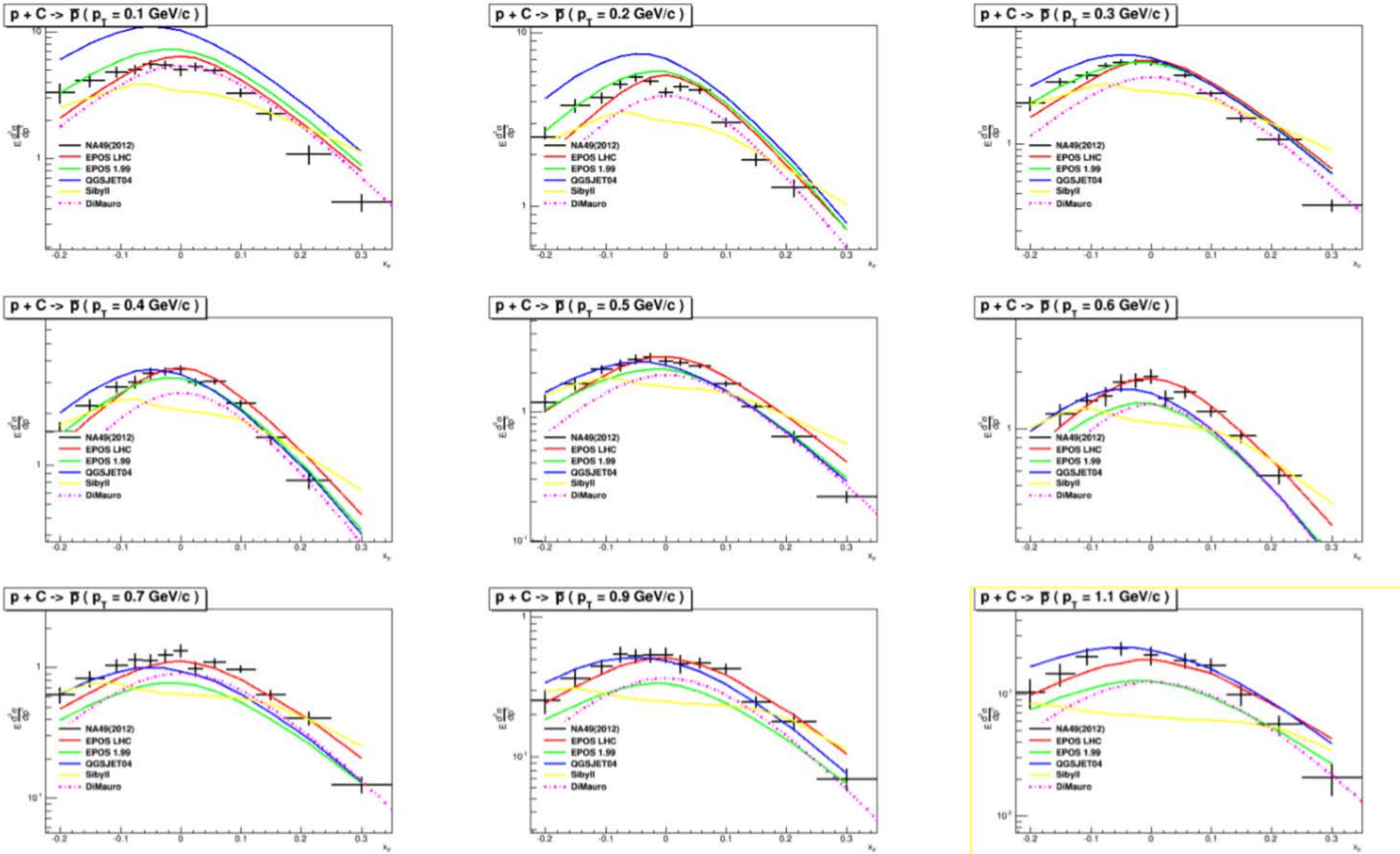
# 相互作用模型的不确定性

# NA49(2010) p(158GeV/c) + p - > ap

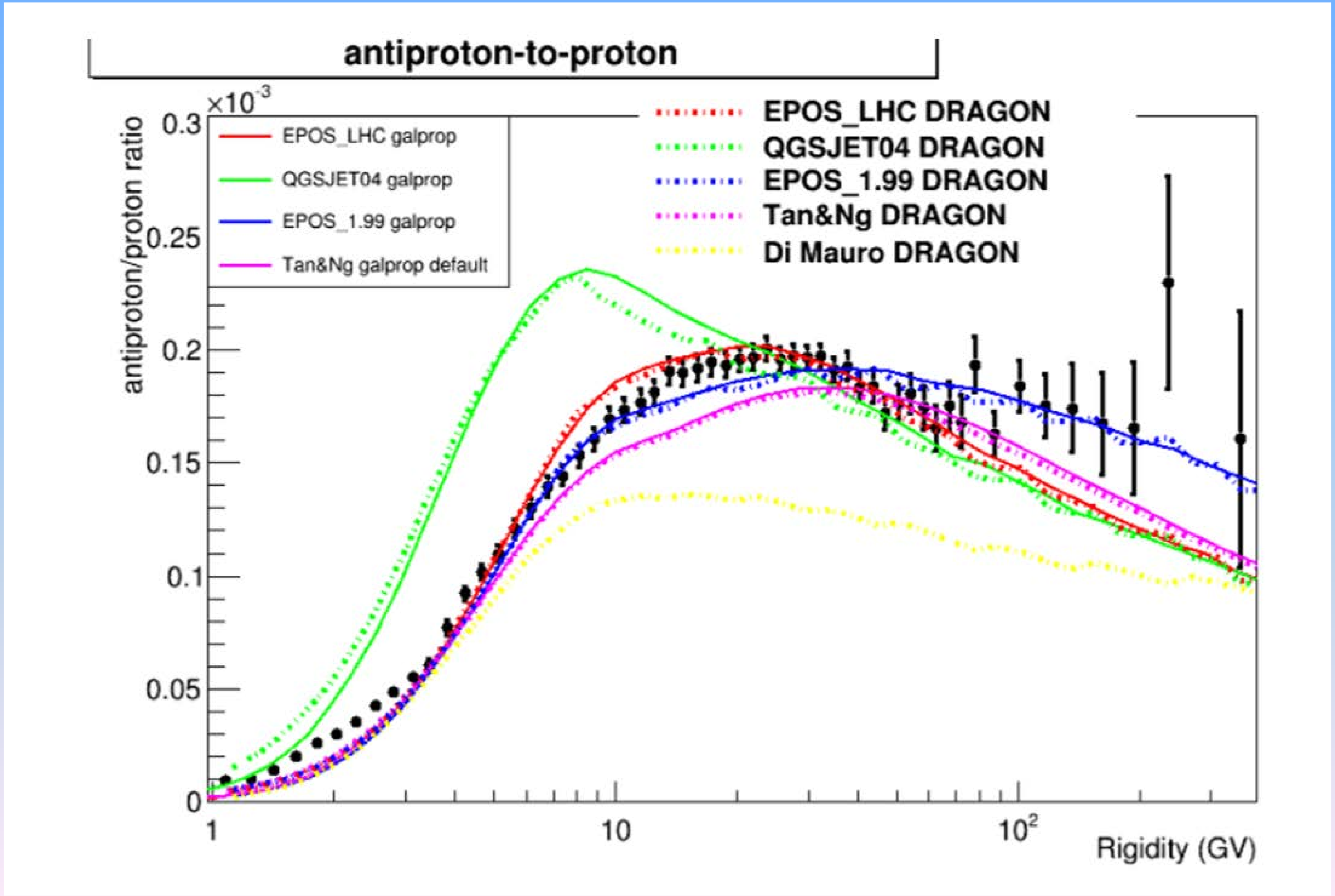


# 相互作用模型不确定性

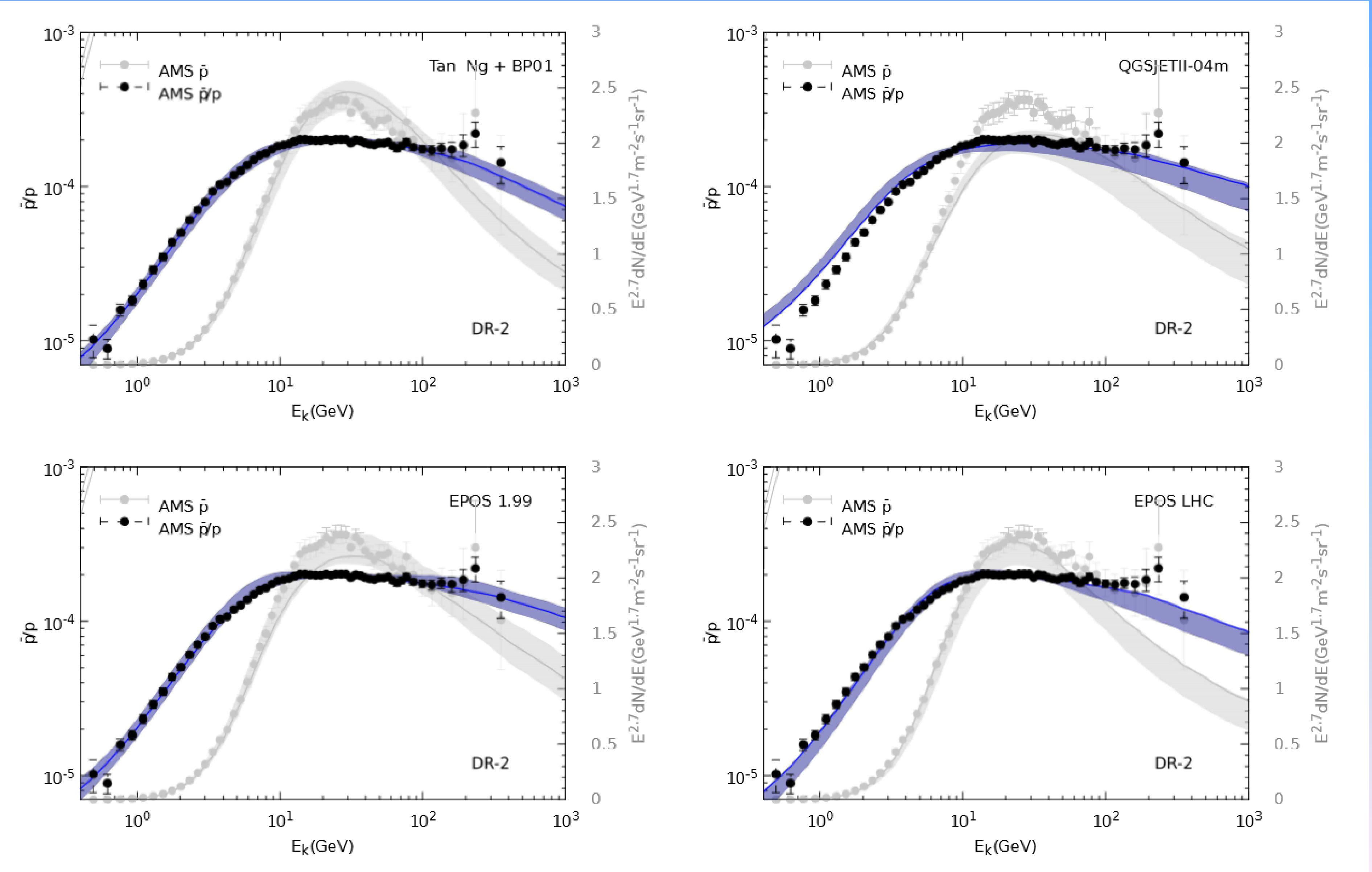
## NA49(2012) p(158GeV/c) + C - > ap



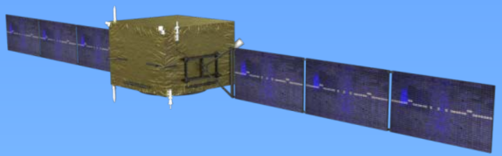
# Pbar/p adopting different interaction model



# Pbar/p adopting different interaction model



# 暗物质卫星简介

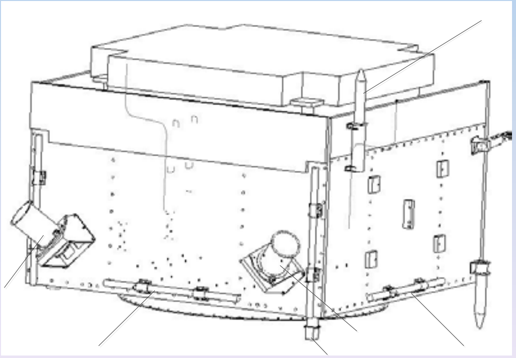


- 暗物质粒子探测卫星（简称DAMPE）是中国科学院空间科学先导专项之一，其主要科学目标是开展高能电子、宇宙线粒子和伽玛射线的观测，进而探寻暗物质存在的证据，并研究其空间分布特性，同时也可开展高能宇宙线、伽马天文的研究。

- 该卫星于2015年12月17日发射。发射后，在轨测试标定工作1~2个月，之后进入常管模式。

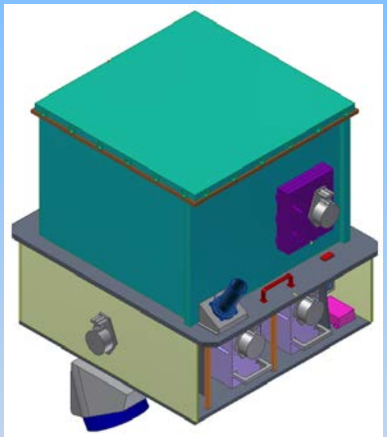
## 高能电子探测指标

- 探测能区：5～10,000GeV；
- 能量分辨率：1.5%@800GeV；
- 本底抑制能力：大于100,000；
- 几何因子：大于$0.3m^2.sr$。

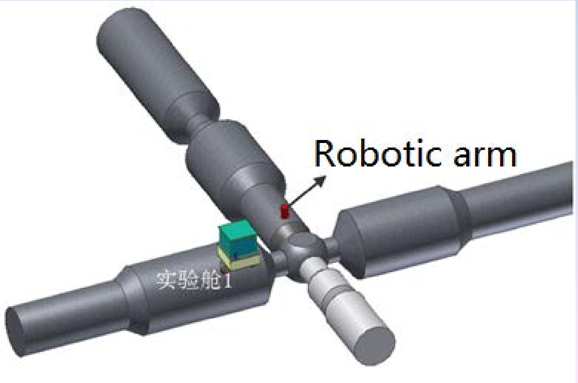


# HERD concept

- **Aim: a flagship and landmark scientific experiment onboard the China's Space Station**
- **Sciences**
  - Indirect dark matter search with unprecedented sensitivity
  - Precise cosmic ray spectrum and composition measurements up to the knee energy
  - Gamma-ray monitoring and survey
- **Unique capabilities**
  - Direct PeV CR observation with best energy resolution
  - Low energy gamma ray observation
  - Largest geometric factors for electrons and cosmic rays



- **Planned launch 2022-2025; 10+ years lifetime**



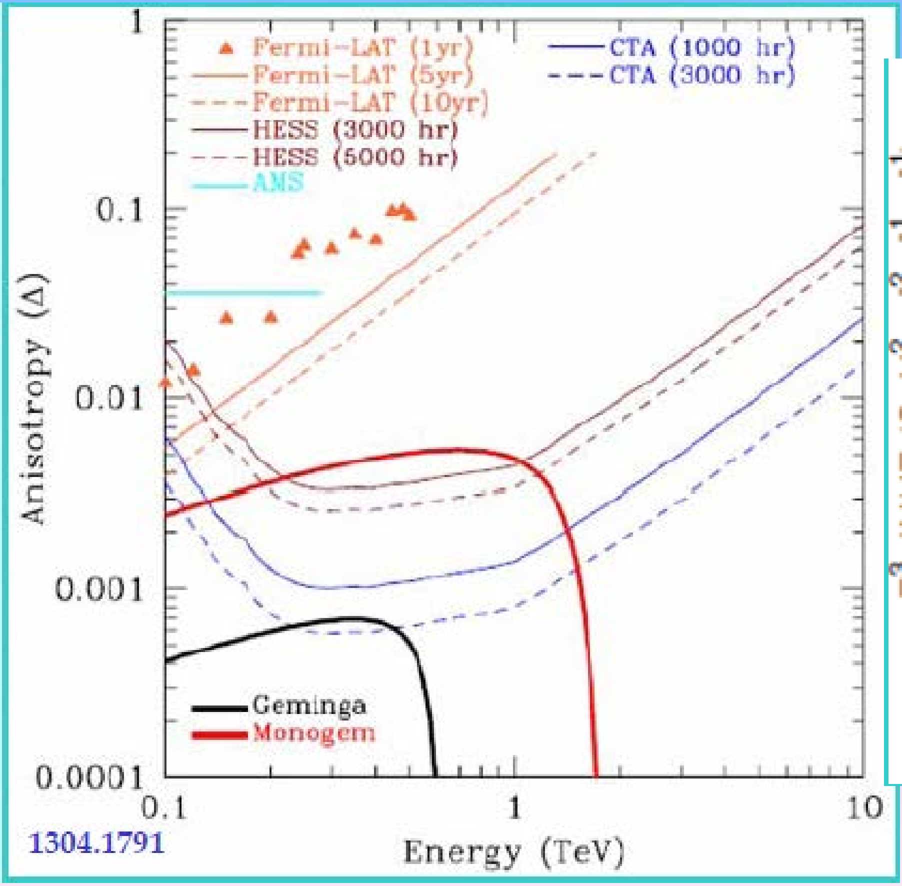
# 总结

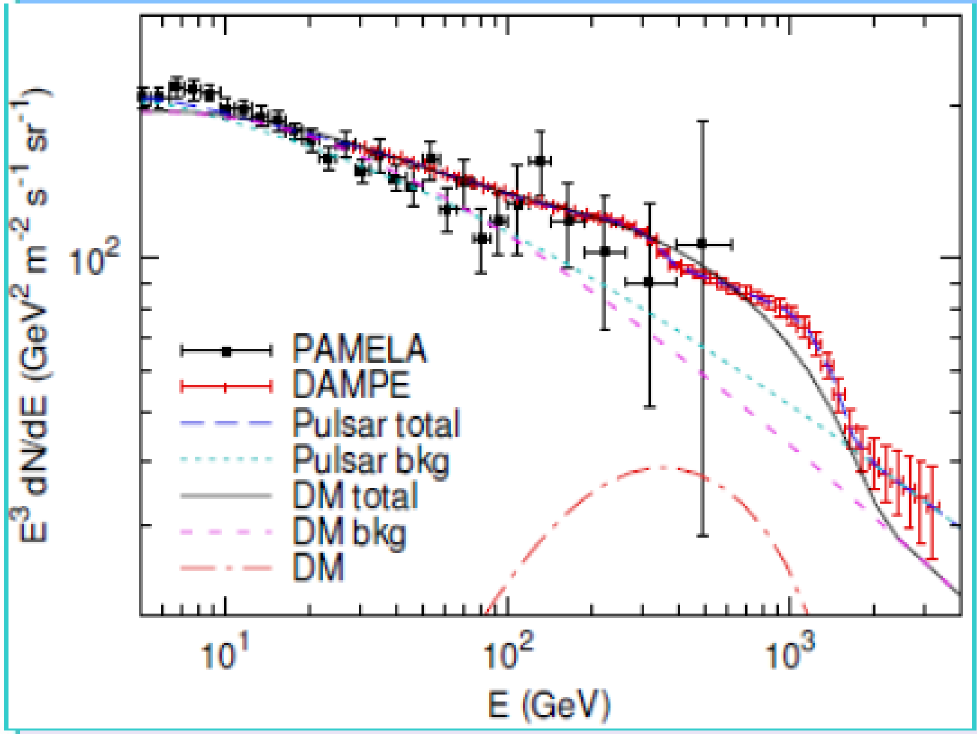
- 有大量实验在不同方向上寻找暗物质信号，目前看来仍然没有发现确信的信号。
- 好的消息，大量的更加精密的实验将开展进一步发寻找：DAMPE, HERD, LHAASO。能够确定宇宙线正电子来源将是一个重要的进展。

# 常用的工具

- Galprop：计算银河系的宇宙线背景，包括反质子、正电子比例，弥散伽马射线本底等。
- DarkSUSY：计算超对称（MSSM）热产生，直接探测、间接探测，可以和PYTHIA、GALPROP等接口
- MicrOMEGA：似乎热产生计算结果更好，SUSY谱计算接口多；可以直接输入新物理的拉氏量计算任意模型的各种过程。
- MadDM: 易于和对撞机研究结合

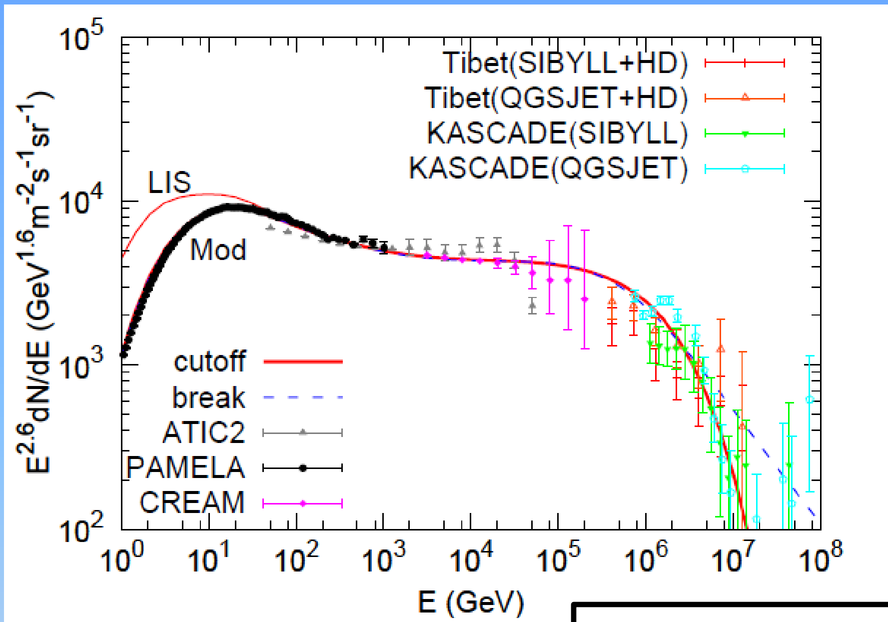
# DM vs pulsar: flux anisotropy vs spectrum wiggles

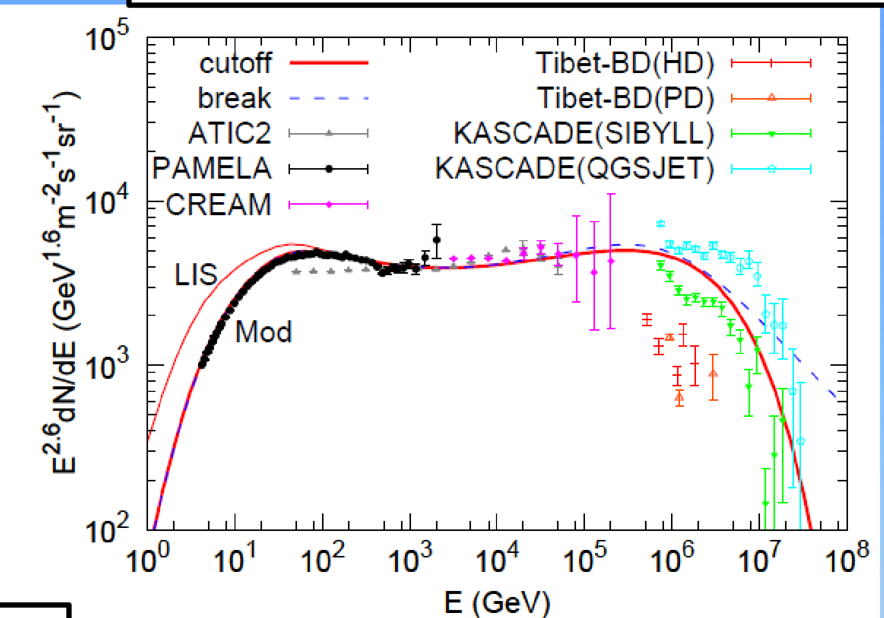


# 改变电子本底谱

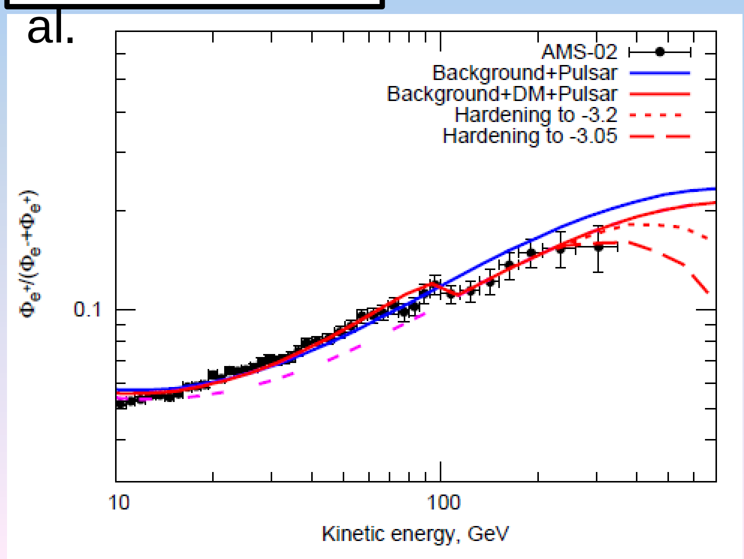
Yuan, Q., Zhang, B, Bi, XJ PRD 84 (2011) 043002

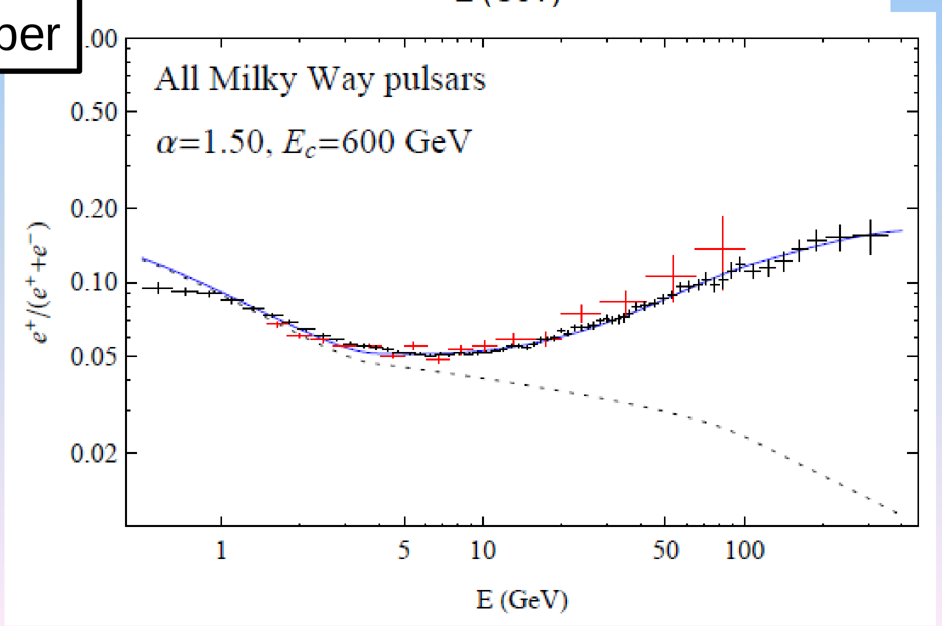


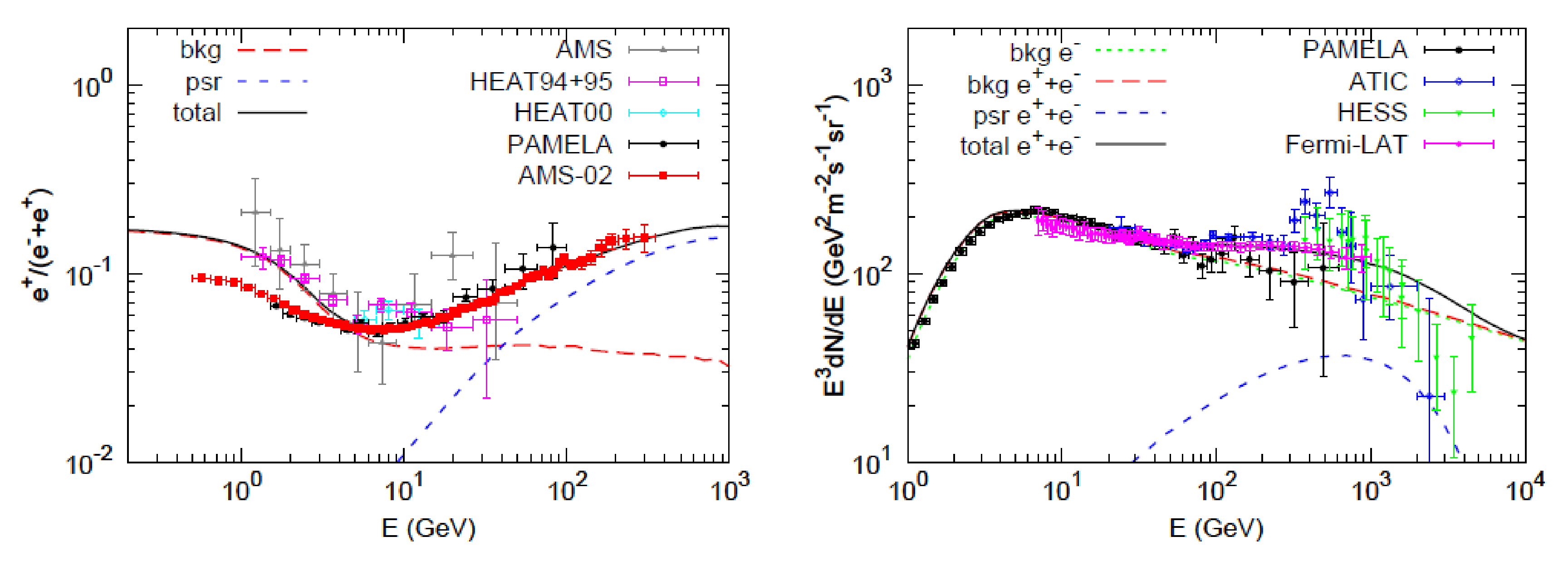

Cholis &Hooper

Feng yang et al.



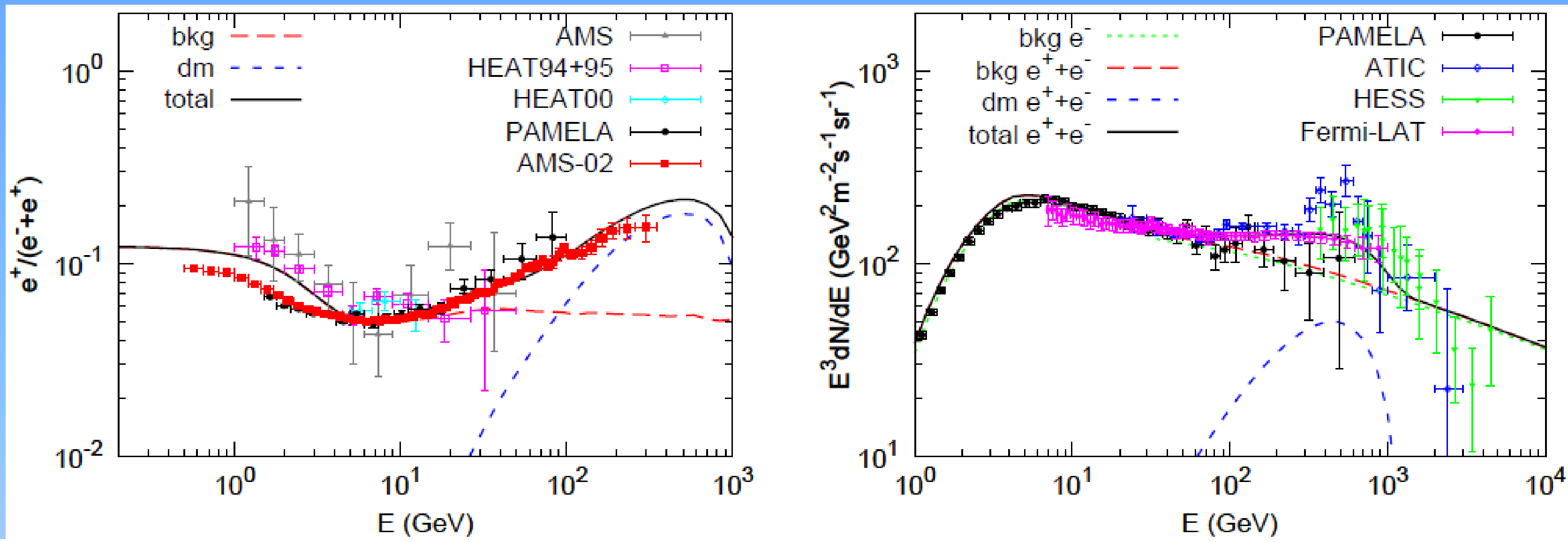



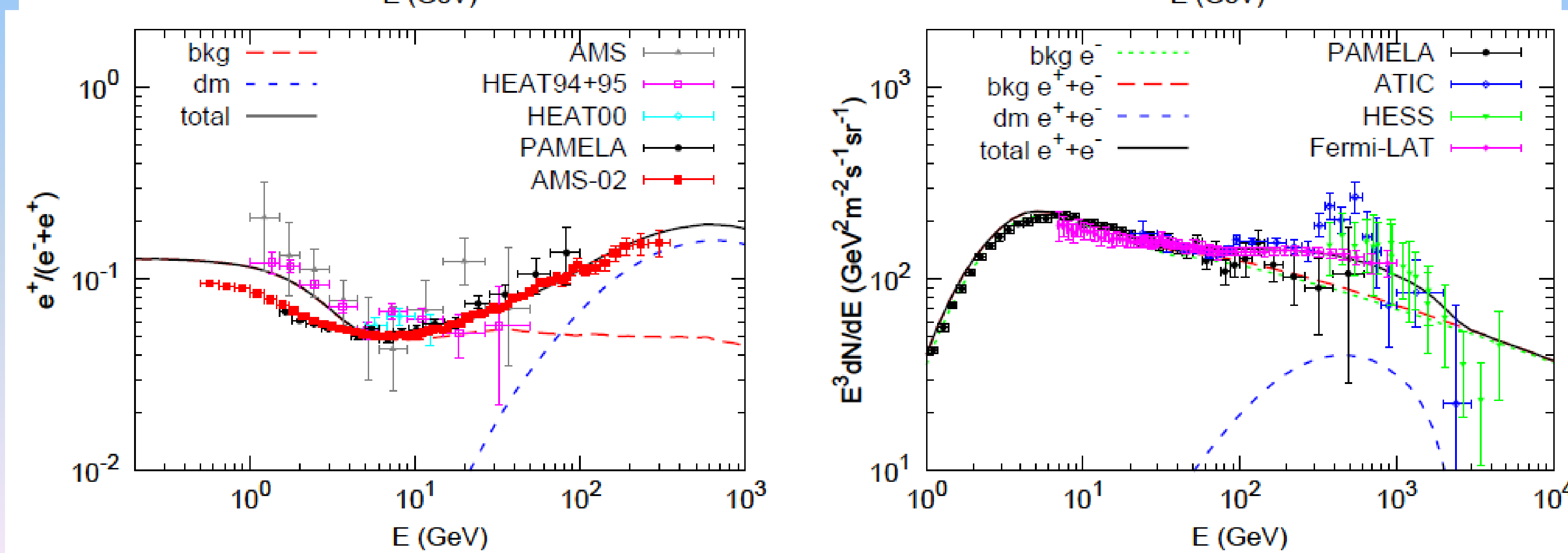
# 到pulsar的结果



bkg
psr
total
AMS
HEAT94+95
HEAT00
PAMELA
AMS-02
e+/(e-+e+)
E (GeV)
bkg e-
bkg e++e-
psr e++e-
total e++e-
PAMELA
ATIC
HESS
Fermi-LAT
E3dN/dE (GeV2m-2s-1sr-1)
E (GeV)

# 暗物质到mu和tau


bkg
dm
total
AMS
HEAT94+95
HEAT00
PAMELA
AMS-02
$e^+/(e^-+e^+)$
E (GeV)
bkg $e^-$
bkg $e^++e^-$
dm $e^++e^-$
total $e^++e^-$
PAMELA
ATIC
HESS
Fermi-LAT
$E^3dN/dE$ ($GeV^2m^{-2}s^{-1}sr^{-1}$)
E (GeV)


bkg
dm
total
AMS
HEAT94+95
HEAT00
PAMELA
AMS-02
$e^+/(e^-+e^+)$
E (GeV)
bkg $e^-$
bkg $e^++e^-$
dm $e^++e^-$
total $e^++e^-$
PAMELA
ATIC
HESS
Fermi-LAT
$E^3dN/dE$ ($GeV^2m^{-2}s^{-1}sr^{-1}$)
E (GeV)

| | $p^e_{\mathrm{br},2} = 230$ GeV | $p^e_{\mathrm{br},2}$ free |
|---|---|---|
| $\chi^2_{\mathrm{min}}/\mathrm{dof}$ | 236.6/150 | 159.0/149 |

| | $\mu^+\mu^-$ | $\tau^+\tau^-$ |
|---|---|---|
| $\chi^2_{\mathrm{min}}/\mathrm{dof}$ | 188.1/150 | 161.3/150 |

| | pulsar | DM ($\mu^+\mu^-$) | DM ($\tau^+\tau^-$) |
|---|---|---|---|
| I-a | 278.7/151 | 506.7/152 | 496.5/152 |

Chi2大大减小到~1，这时可以很好拟合数据