Dark Matter

Evidence For Dark Matter

- Dark Matter

  = matter without emitting lights

- Dark matter in galaxies

  - Rotation curve

    rotation velocity

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

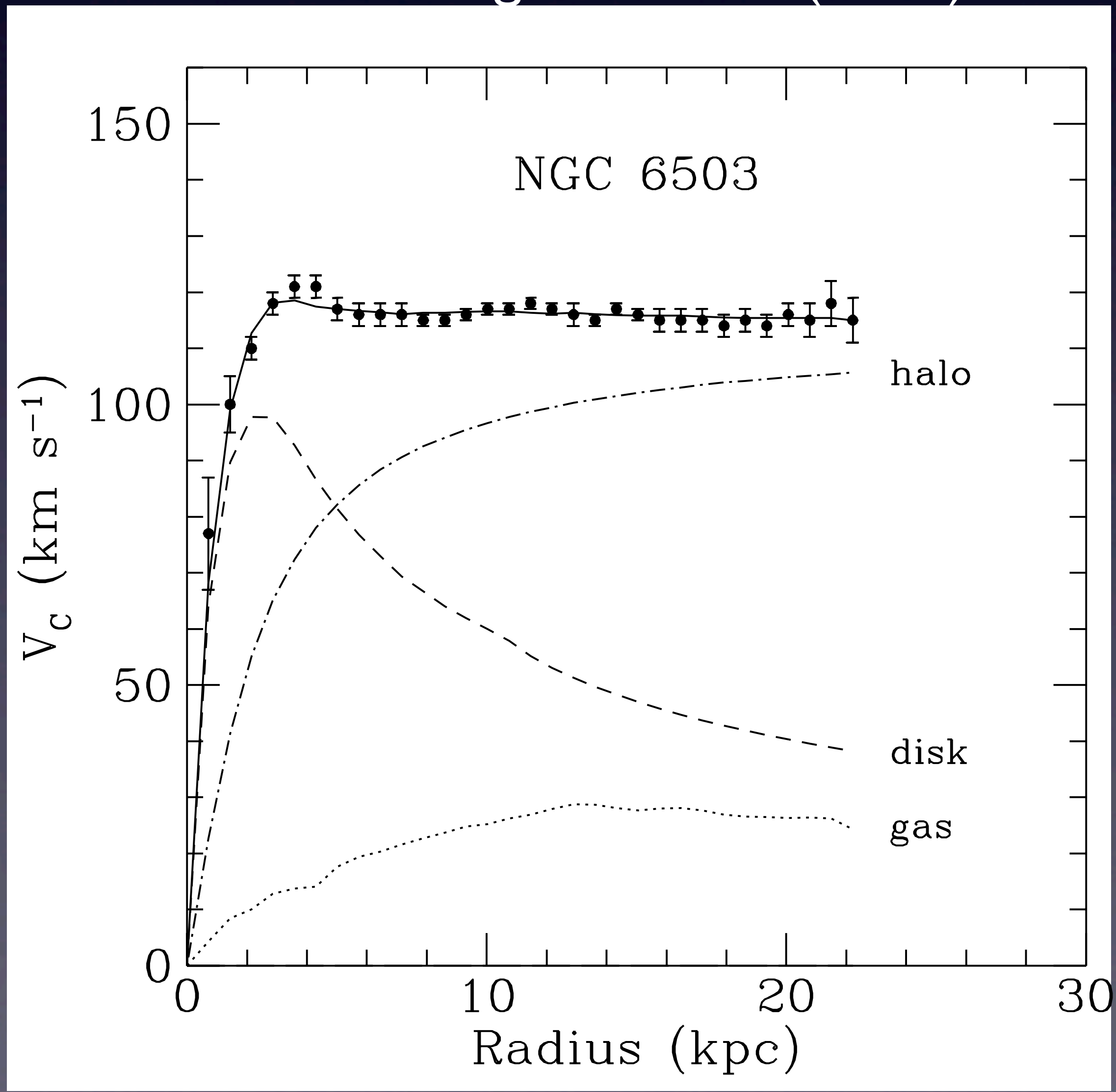
If the mass is dominated by stars

v ~ r$^{-1/2}$ beyond the luminous part

In fact,

$$\boxed{v = \text{const} \quad (M(r) \sim r)}$$

Begeman et al (1991)



Evidence For Dark Matter (2)

- Dark Matter in Clusters of Galaxies
  - X-ray emission from gas in a cluster

Hydrostatic equilibrium $$\frac{dP}{dr} = -\frac{GM(r)\rho}{r^2} \qquad (P : \text{ pressure})$$

Equation of state $$P = \frac{k_B T \rho}{\mu m_p} \qquad (\mu : \text{ mean molecular weight})$$

$$\Rightarrow \quad M(r) = \frac{k_B T r}{G \mu m_p}\left[-\frac{d\ln\rho}{d\ln r} - \frac{d\ln T}{d\ln r}\right]$$

$\rho \propto r^{-(1.5-2)}$

$$\Rightarrow \quad \boxed{M(r) \simeq 10^{15} M_\odot \left(\frac{r}{\text{Mpc}}\right)\left(\frac{T}{10\text{keV}}\right)}$$

O(10) larger than baryon mass of a cluster

Evidence For Dark Matter (3)

- Dark Matter on Cosmological Scales
  - CMB Temperature Fluctuation

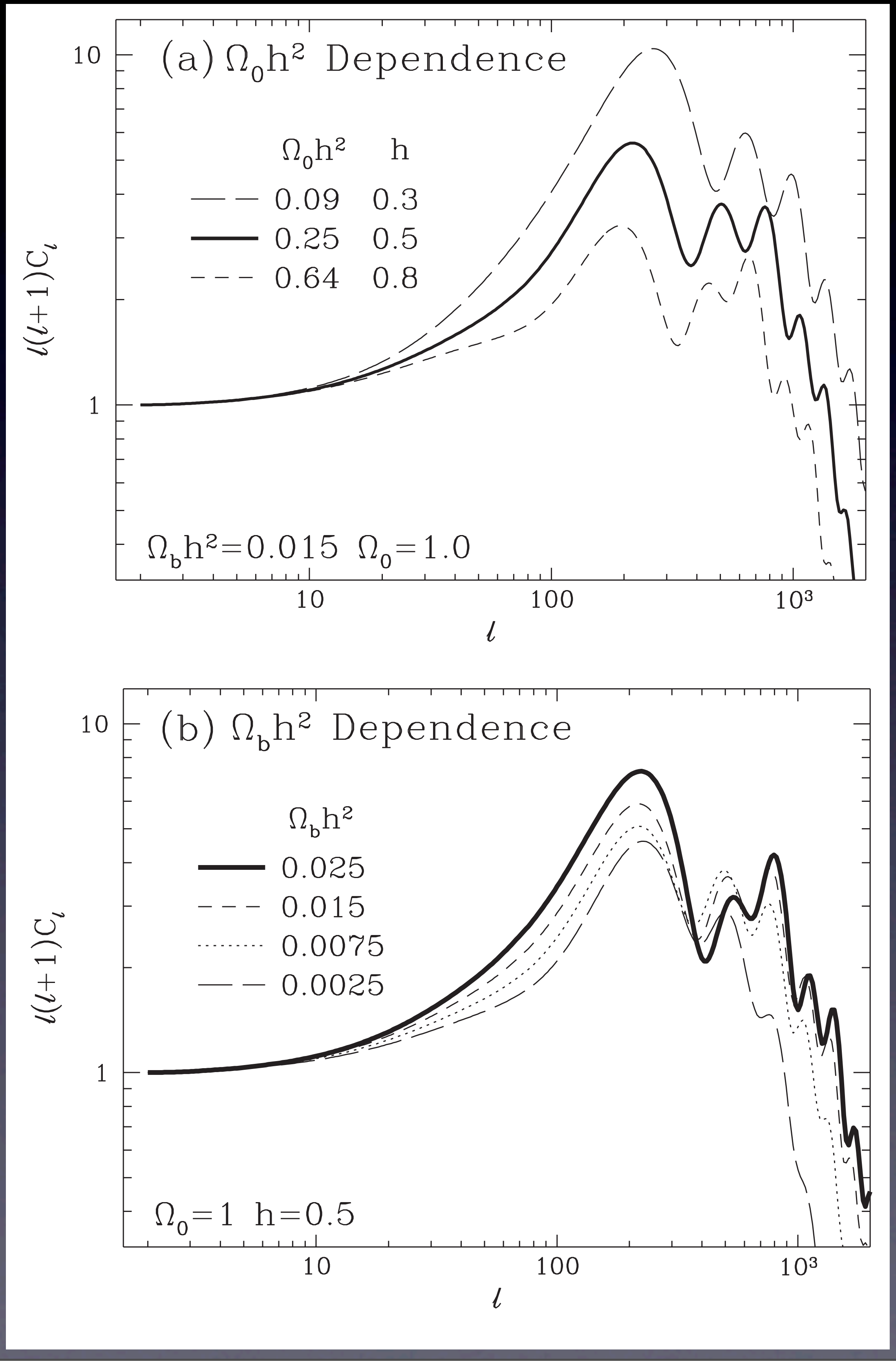
$$\frac{\delta T}{T}(\theta,\phi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta,\phi)$$

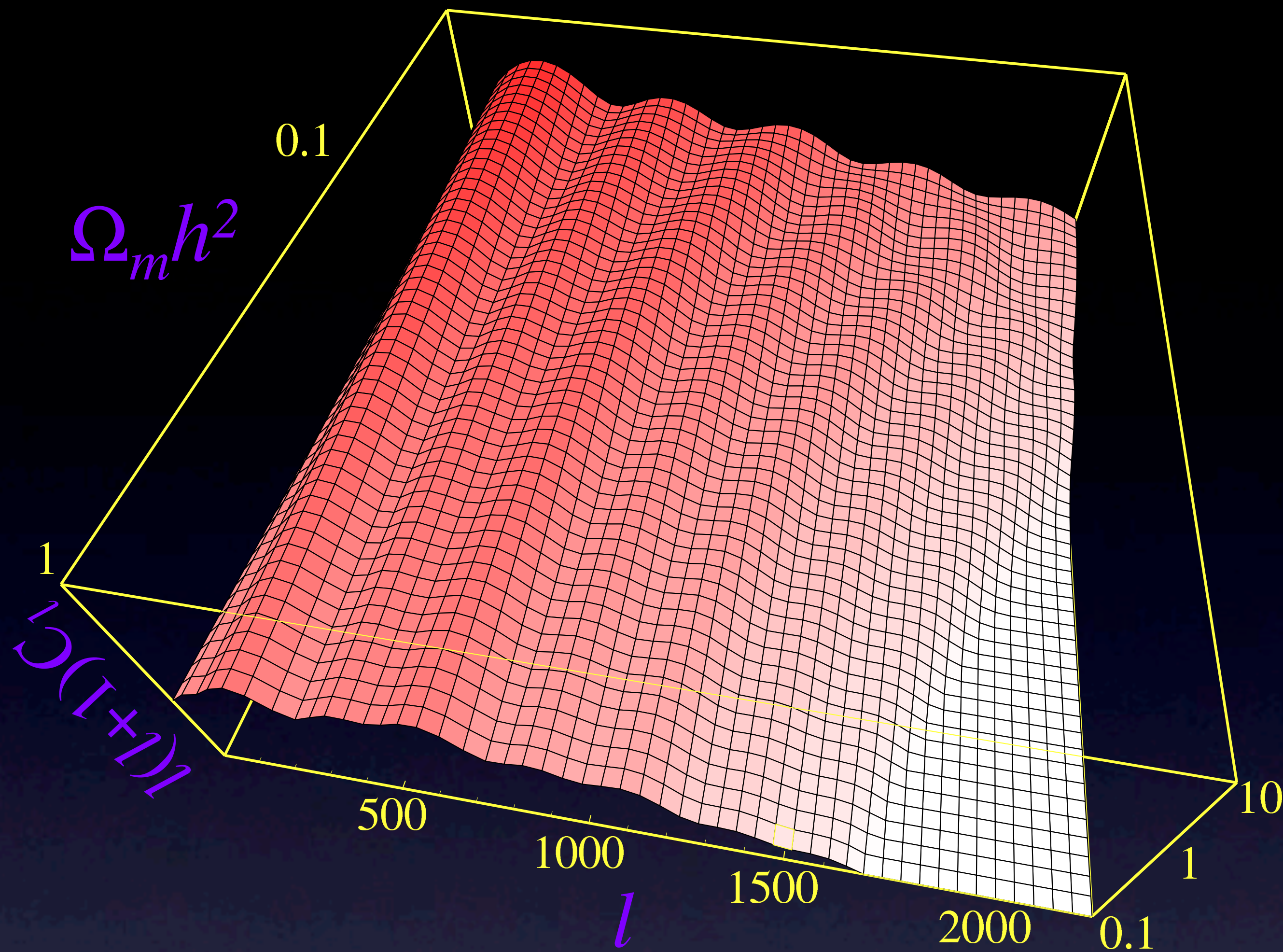
$Y_{\ell m}(\theta,\phi)$: Spherical harmonics

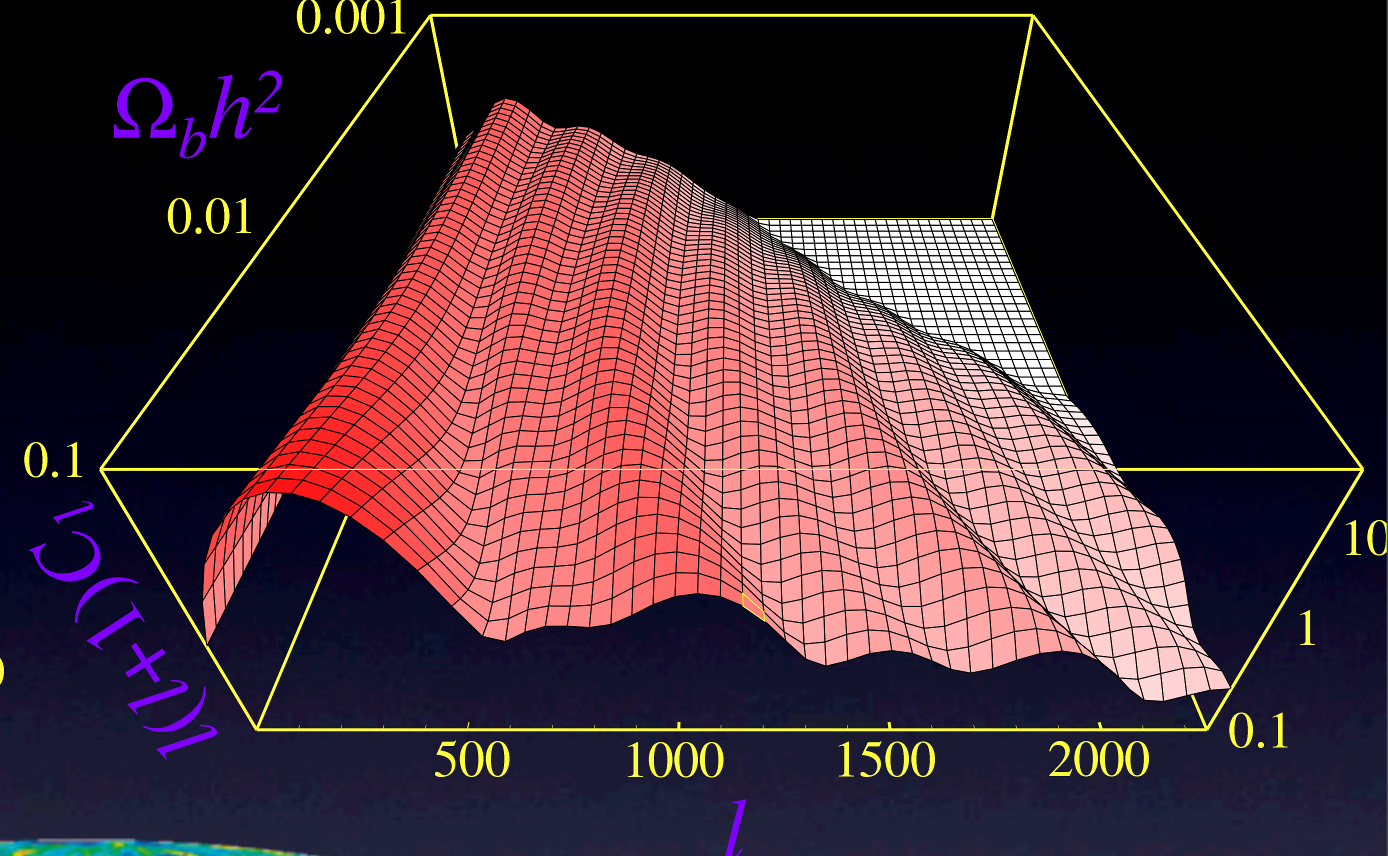
$$C_\ell = \langle |a_{\ell m}|^2 \rangle = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

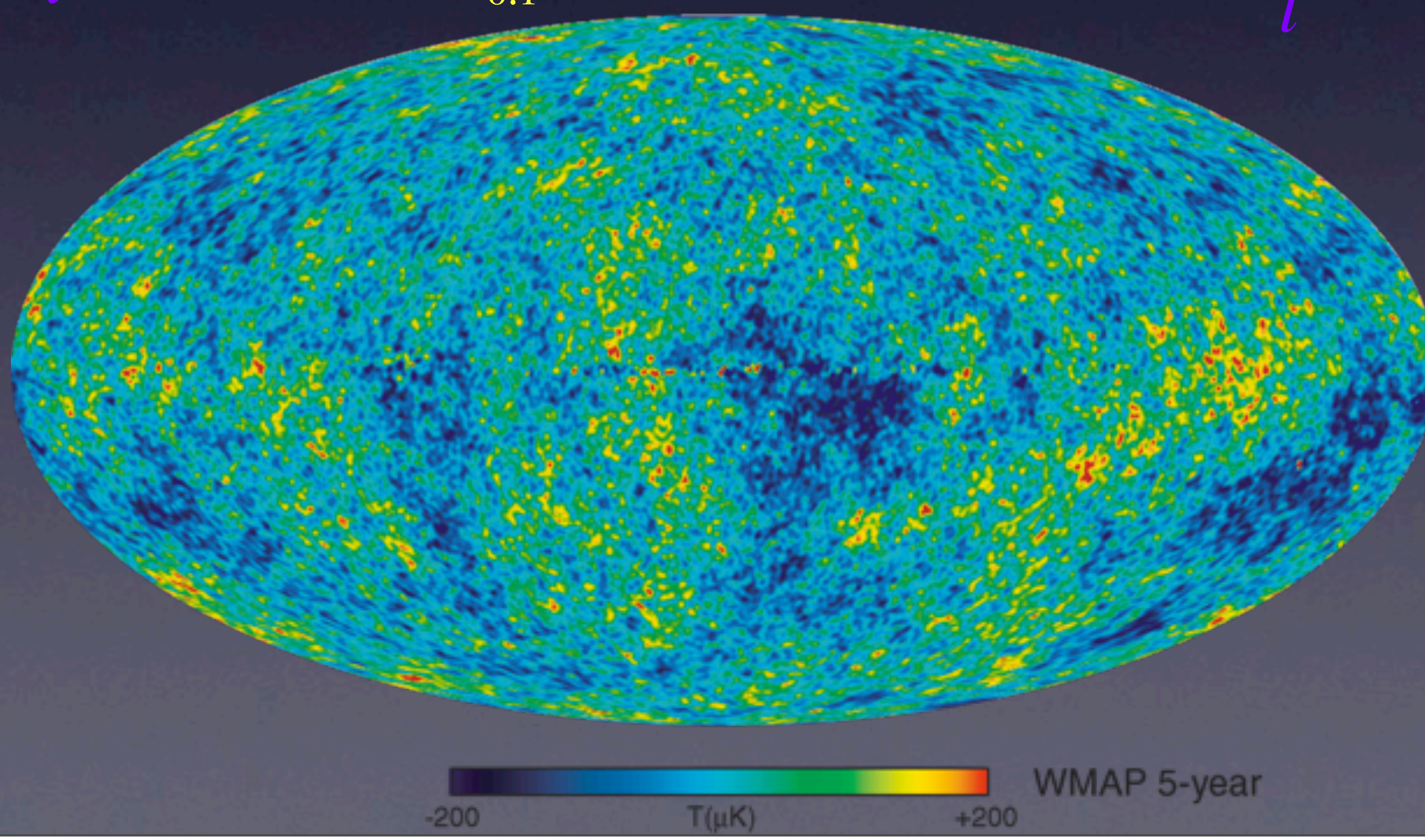
$$\boxed{\begin{aligned} \Omega_m h^2 &= 0.1369 \pm 0.0037 \\ \Omega_b h^2 &= 0.02265 \pm 0.00059 \end{aligned}}$$

Hu, White (1996)




0.1
$\Omega_m h^2$
1
$l(l+1)C_l$
500
1000
1500
2000
l
10
1
0.1

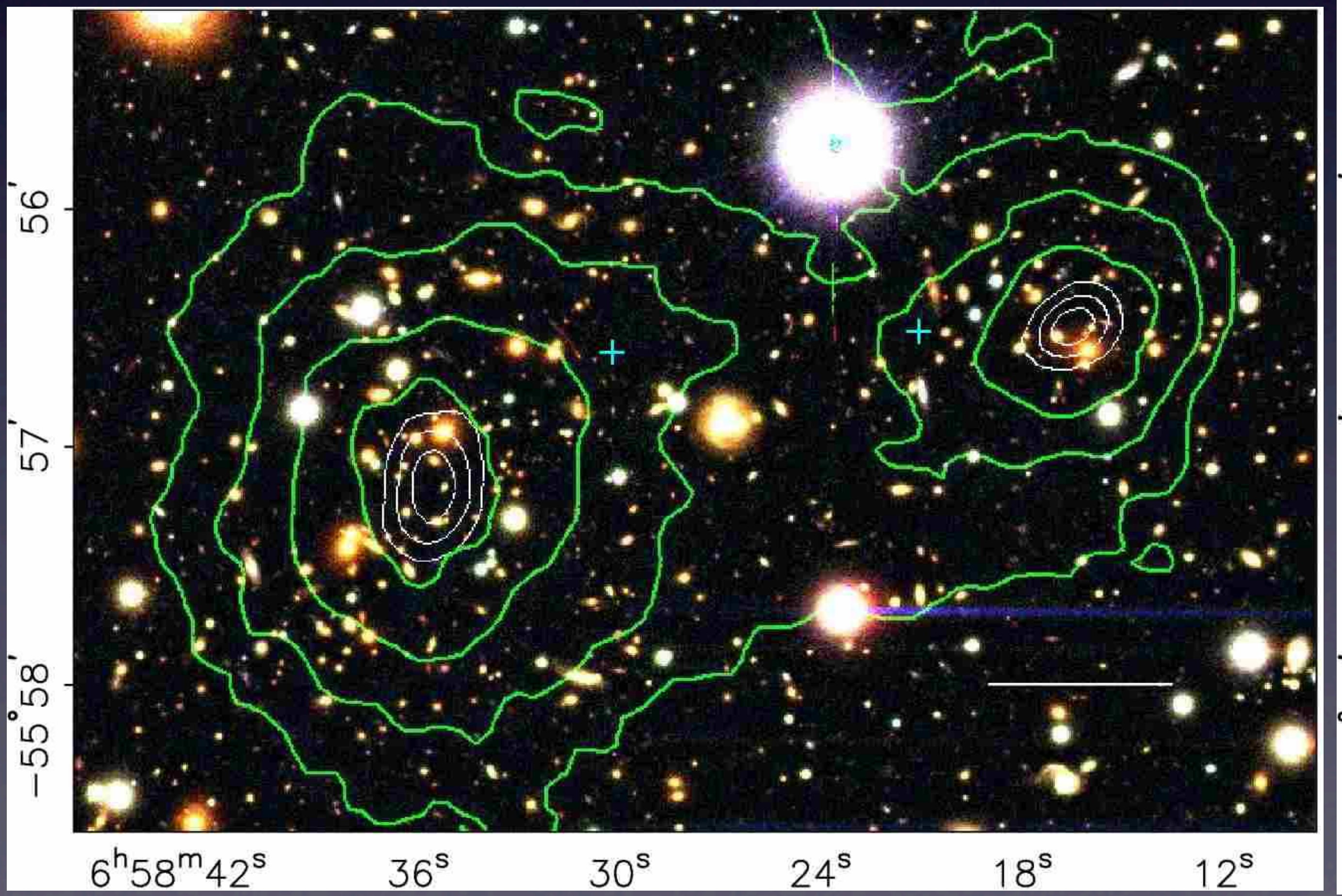

0.001
$\Omega_b h^2$
0.01
0.1
$l(l+1)C_l$
500
1000
1500
2000
l
10
1
0.1

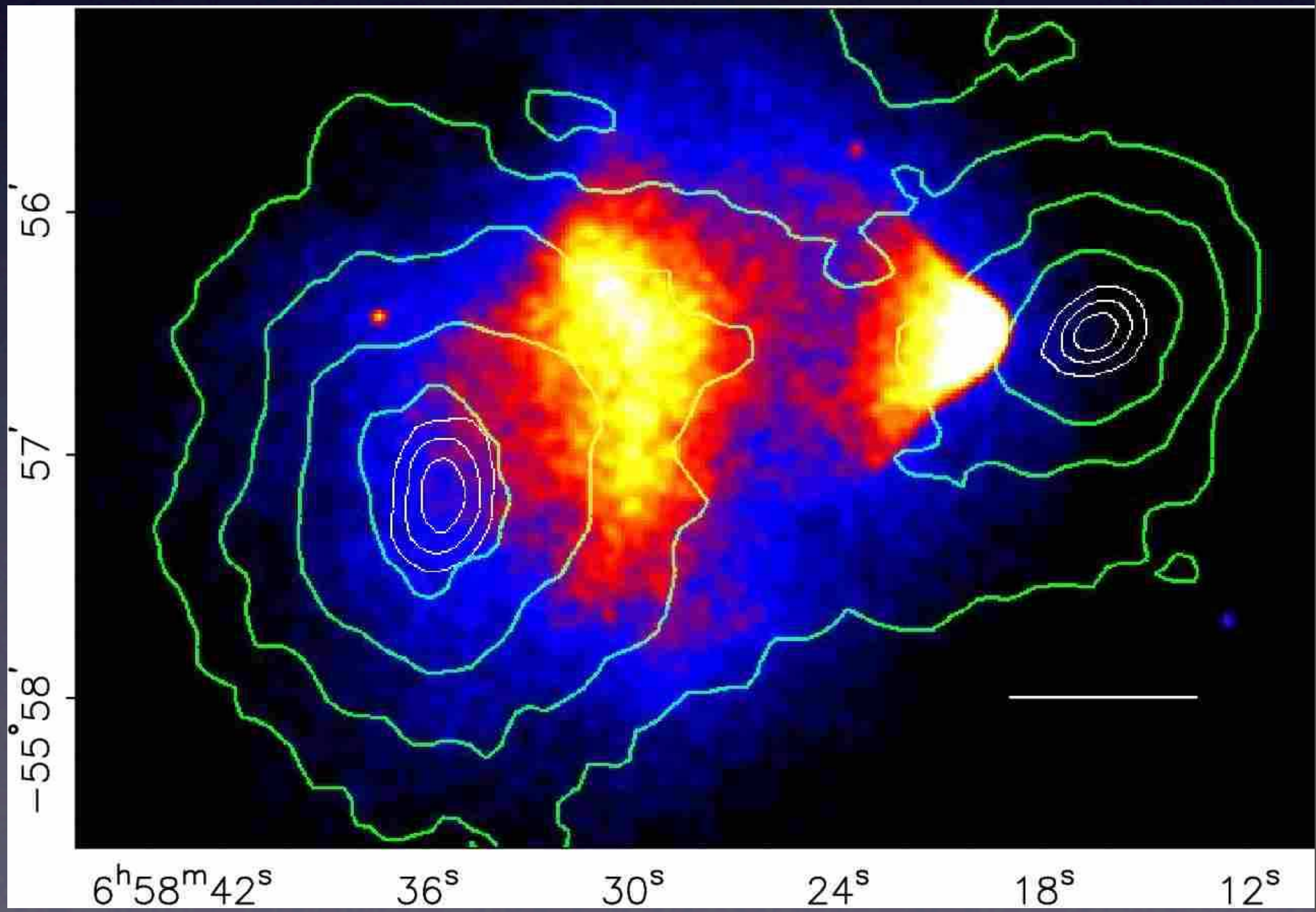

WMAP 5-year
-200
T(μK)
+200

Best Evidence against Modified Gravity

- Cluster of Galaxies 1E 0657-56
  - Gas distribution (X-ray)
  - Dark Matter distribution (gravitational lens)

Clowe et al (2006)





X-ray

Dark Matter Candidate

- SUSY Particle
  - Neutralino
  - Gravitino
- Axion
- Kaluza-Klein states
- Q Ball
- Black hole . . . . .

- Particle DM
  - Thermal Relics
    - Neutralino
  - Non-thermal
    - Axion , Gravitino
- Astrophysical Object
  - Black hole

Cosmic Density of Thermal Relics

- Stable DM particles which were in thermal equilibrium

$$X + \bar{X} \longleftrightarrow f + \bar{f}$$

- number density n_X is determined by Boltzmann eq.

$$\boxed{\frac{dn_X}{dt} = \underbrace{-3\frac{\dot{a}}{a}n_X}_{\text{cosmic exp.}} - \langle\sigma v\rangle(\underbrace{n_X^2}_{\text{annihilation}} - \underbrace{n_{X,eq}^2}_{\text{creation}})}$$

$$\langle\sigma v\rangle n_X \gg H \qquad \Rightarrow \qquad n_X = n_{X,eq}(T)$$

$$\langle\sigma v\rangle n_X \ll H \qquad \Rightarrow \qquad n_X \propto a^{-3} \propto T^3$$

$\langle\sigma v\rangle n_X \simeq H$ ➡ X particle dcouple from thermal bath and their comoving density freezes

➡ T_f : freezeout temperature

(A) Decouple when X is relativistic

- At decouple

$$n_X = g_X \frac{\zeta(3)}{\pi^2} T^3 \qquad\qquad g_X = \begin{cases} \frac{3}{4} g_s & \text{fermion} \\ g_s & \text{boson} \end{cases}$$

- Photons are heated up through particle-antiparticle annihilation after X decouples

$$\Rightarrow \quad \boxed{n_{X,0} = \left(\frac{n_X}{s}\right)_{T_f} s_0 = \frac{45\zeta(3) g_X}{2\pi^4 g_{*s}} s_0}$$

$$\rho_{\mathrm{cr},0}/s_0 = 1.74 \times 10^{-9}\,\mathrm{GeV}$$

$$\boxed{\Omega_X = m_X \frac{n_{X,0}}{\rho_{\mathrm{cr},0}} = 0.152 \frac{g_X}{g_{*s}} \left(\frac{m_X}{\mathrm{eV}}\right)}$$

(B) Decouple when X is non-relativistic

- Boltzmann eq.

$$\boxed{\frac{dn_X}{dt} = -3\frac{\dot{a}}{a}n_X - \langle\sigma v\rangle(n_X^2 - n_{X,eq}^2)}$$

$$f = n_X/T \quad y = T/m_X \qquad dt = -\sqrt{\frac{45}{8\pi^3 G g_*}}T^{-3}dT$$

$$\rightarrow \frac{df}{dy} = \sqrt{\frac{45}{8\pi^3 G g_*}} m_X \langle\sigma v\rangle (f^2 - f_{eq}^2)$$

$$f_{eq} = \frac{g_s}{\sqrt{8\pi^3}} e^{-1/y} y^{-3/2}$$

$f \simeq f_{eq}$ until decoupling

$$\frac{df_{eq}}{dy} = \sqrt{\frac{45}{8\pi^3 G g_*}} m_X \langle\sigma v\rangle f_{eq}^2 \Big|_{y=y_{eq}}$$

$$\rightarrow \boxed{y_f \simeq \left[\ln\left(\sqrt{\frac{45}{8\pi^3 G g_*}} m_X g_s \langle\sigma v\rangle\right) - \frac{1}{2}\ln\left\{\ln\left(\sqrt{\frac{45}{8\pi^3 G g_*}} m_X g_s \langle\sigma v\rangle\right)\right\}\right]^{-1}}$$

$y < y_f \;\Rightarrow\; f \gg f_{eq}$ $$\frac{df}{dy} = \sqrt{\frac{45}{8\pi^3 G g_*}} m_X \langle \sigma v \rangle f^2$$

$$\rightarrow \quad f(y) = \left[f_{eq}(y_f)^{-1} + \sqrt{\frac{45}{8\pi^3 G g_*}} m_X \langle \sigma v \rangle (y_f - y) \right]^{-1}$$

$$\simeq \frac{1}{\sqrt{\frac{45}{8\pi^3 G g_*}} m_X \langle \sigma v \rangle y_f}$$

$$\rightarrow \quad \boxed{n_X \simeq \frac{T_X^3}{\sqrt{\frac{45}{8\pi^3 G g_*}} m_X \langle \sigma v \rangle y_f}}$$

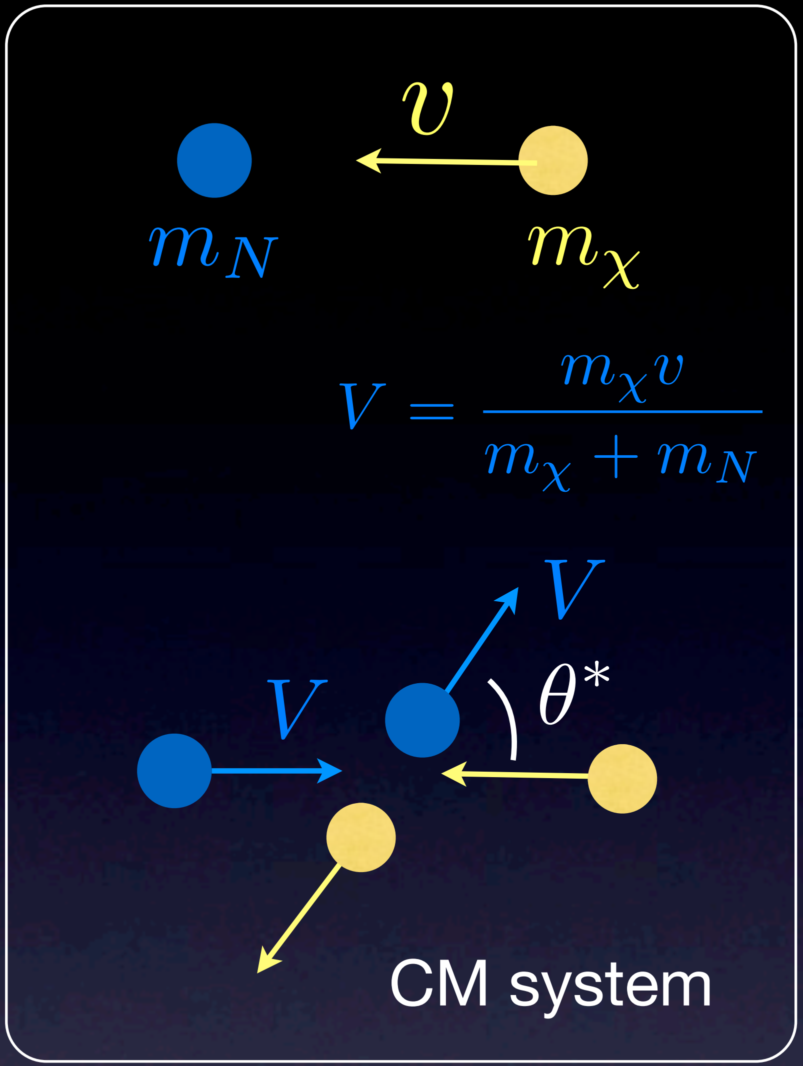
$$\Omega_X = m_X \left(\frac{n_X}{s} \right) \left(\frac{s_0}{\rho_{\mathrm{cr},0}} \right), \quad s = \frac{2 g_{s*} \pi^2}{45} T_X^3, \quad \rho_{\mathrm{cr},0}/s_0 = 1.74 \times 10^{-9} \mathrm{GeV}$$

$$\boxed{\Omega_X = \frac{g_*^{1/2}}{g_{*s} y_f} \left(\frac{\langle \sigma v \rangle}{6.6 \times 10^{-38} \mathrm{cm}^2} \right)^{-1}}$$

Dark Matter Search

- Direct search
  - WIMP-Nucleus elastic scattering
    - Cross section σ_0
    - Energy transferred to the nucleus

$$Q = \frac{m_\chi^2 m_N v^2}{(m_\chi + m_N)^2}(1 - \cos\theta^*)$$

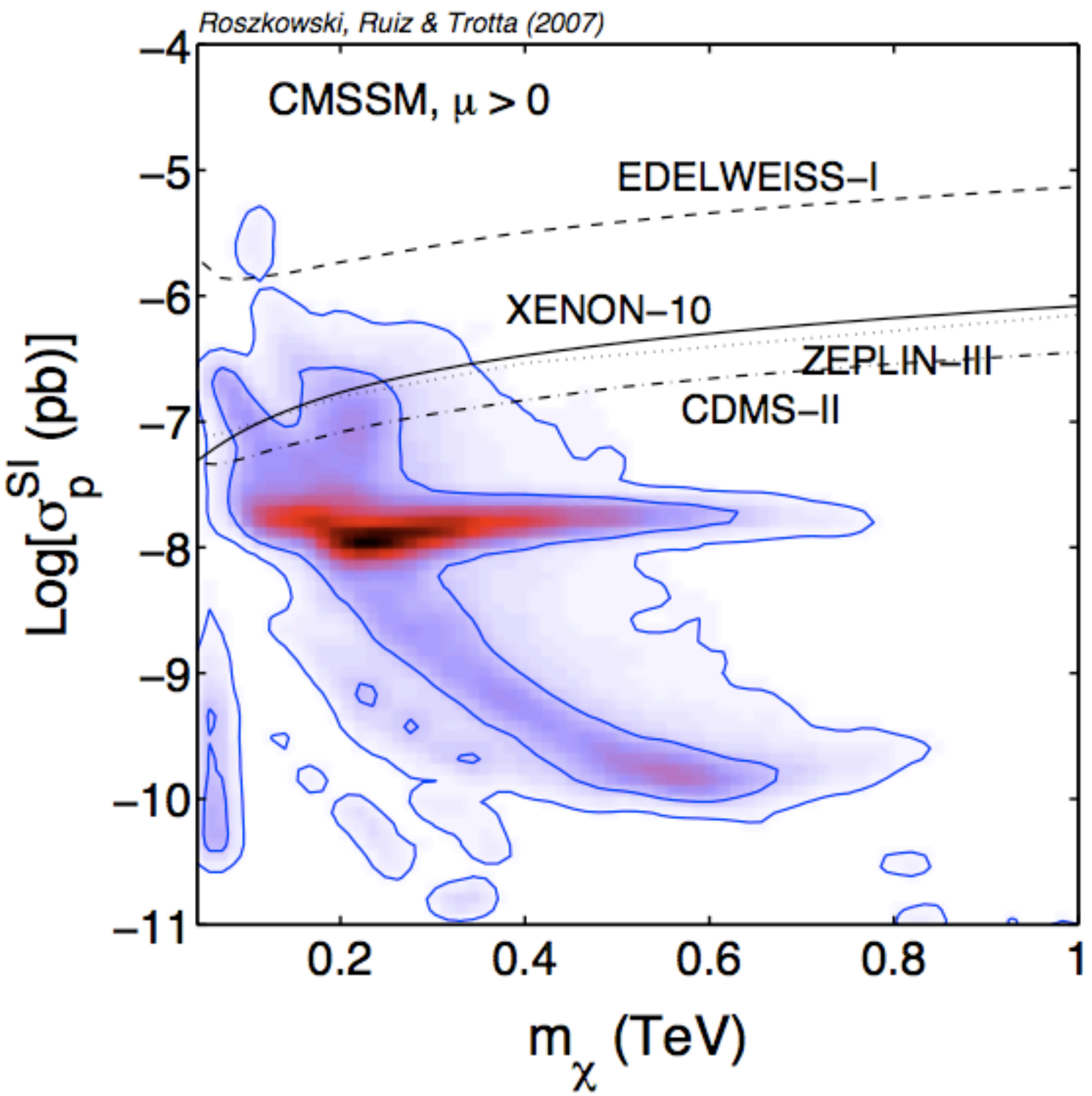


$$m_\chi \sim 100\text{GeV}, \quad m_N \sim 100\text{GeV}, \quad v = 270\text{km/s} \;\Rightarrow\; Q \sim 20\text{keV}$$

→ $\boxed{Q \simeq 1 - 100\text{keV}}$ → Scintillation
Phonon
Ionization

- Typical Rate 10^{-4} - 1 event/kg

Current Limit



Focus on leading/example experiments

Bolometric Detectors

CDMS
Edeleiss
CRESST

Liquid Noble Gas

XENON 10, 100 (LXe)
ZEPLIN III (LXe)
ArDM, WARP (LAr)

Annual modulation, NaI

DAMA

Spooner (COSMO09)

For spin-independent interaction

$$\frac{d\sigma}{d|\mathbf{q}|^2} = \frac{1}{\pi v^2}[Zf_p + (A-Z)f_n]^2 F(Q)$$

$Q = |\mathbf{q}|^2/(2m_N)$ $\quad$ $\mathbf{q}$: momentum transferred

Dark Matter Search

- Indirect search
  - Observing the radiation produced in dark matter annihilation
  - Annihilation rate is proportional to square of the dark matter density

$$\Gamma_A \propto \rho_{\mathrm{DM}}^2$$

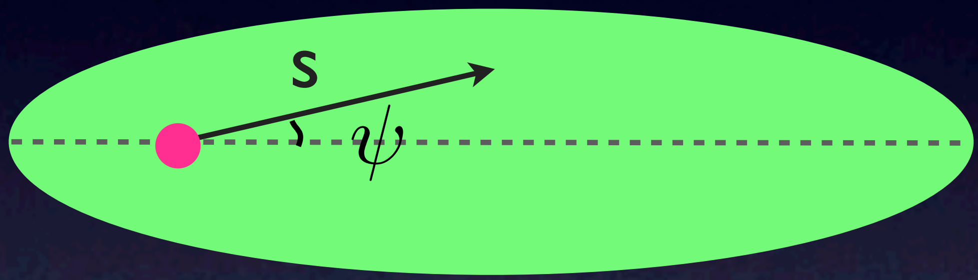
    - Gamma rays and neutrino from the Galactic center
    - High energy neutrinos from the Sun
    - Positrons and anti-protons from the Galactic halo

Gamma rays and neutrinos from Galactic center

- Observed Flux

$$\Phi(\psi, E) = \langle \sigma v \rangle \frac{dN}{dE} \frac{1}{4\pi m_{\mathrm{DM}}^2} \int_{\text{line of sight}} ds \rho^2(r(s,\psi))$$

spectrum of 2nd. particles per annihilation



$$J(\psi) = \frac{1}{8.5\mathrm{kpc}} \left(\frac{1}{0.3\mathrm{GeV/cm}^3} \right)^2 \int_{\text{line of sight}} ds \rho^2(r(s,\psi))$$

$$\Phi(\psi, E) \simeq 5.6 \times 10^{-12} \frac{dN}{dE} \left(\frac{\langle \sigma v \rangle}{\mathrm{pb}} \right) \left(\frac{1\mathrm{TeV}}{m_{\mathrm{DM}}} \right)^2 \bar{J}(\Delta\Omega) \Delta\Omega \mathrm{cm}^{-2} \mathrm{s}^{-1}$$

$\bar{J}(\Delta\Omega)$: average of $J(\psi)$ over a spherical region of solid angle $\Delta\Omega$

High Energy Neutrino from the Sun

- DM particles are captured in gravitational well of Sun or Earth and can annihilate at large rate
- WIMP number N in the core of the SUN

$$\boxed{\dot{N} = C^{\odot} - A^{\odot} N^2}$$

$$k_B T_{\odot} \sim \frac{G m_{\mathrm{DM}} \rho_{\odot} V_{\mathrm{eff}}}{V_{\mathrm{eff}}^{1/3}}$$

$C^{\odot}$: Capture rate

$$A^{\odot} = \frac{\langle \sigma v \rangle}{V_{\mathrm{eff}}}$$

V_{eff} : effective volume

$$\boxed{V_{\mathrm{eff}} = 5.7 \times 10^{27} \mathrm{cm}^3 \left(\frac{100\mathrm{GeV}}{m_{\mathrm{DM}}} \right)^{3/2}}$$

$$\boxed{N = \sqrt{\frac{C^{\odot}}{A^{\odot}}} \tanh(\sqrt{C^{\odot} A^{\odot}} t_{\odot})}$$

$t_{\odot} \simeq 4.5$ billion years

$$C^{\odot}A^{\odot}t_{\odot} \gg 1 \quad \Rightarrow \quad N = (C^{\odot}/A^{\odot})^{1/2}$$

- WIMP annihilation rate

$$\boxed{\Gamma = \frac{1}{2}A^{\odot}N^2 = \frac{1}{2}C^{\odot}}$$

- Capture rate

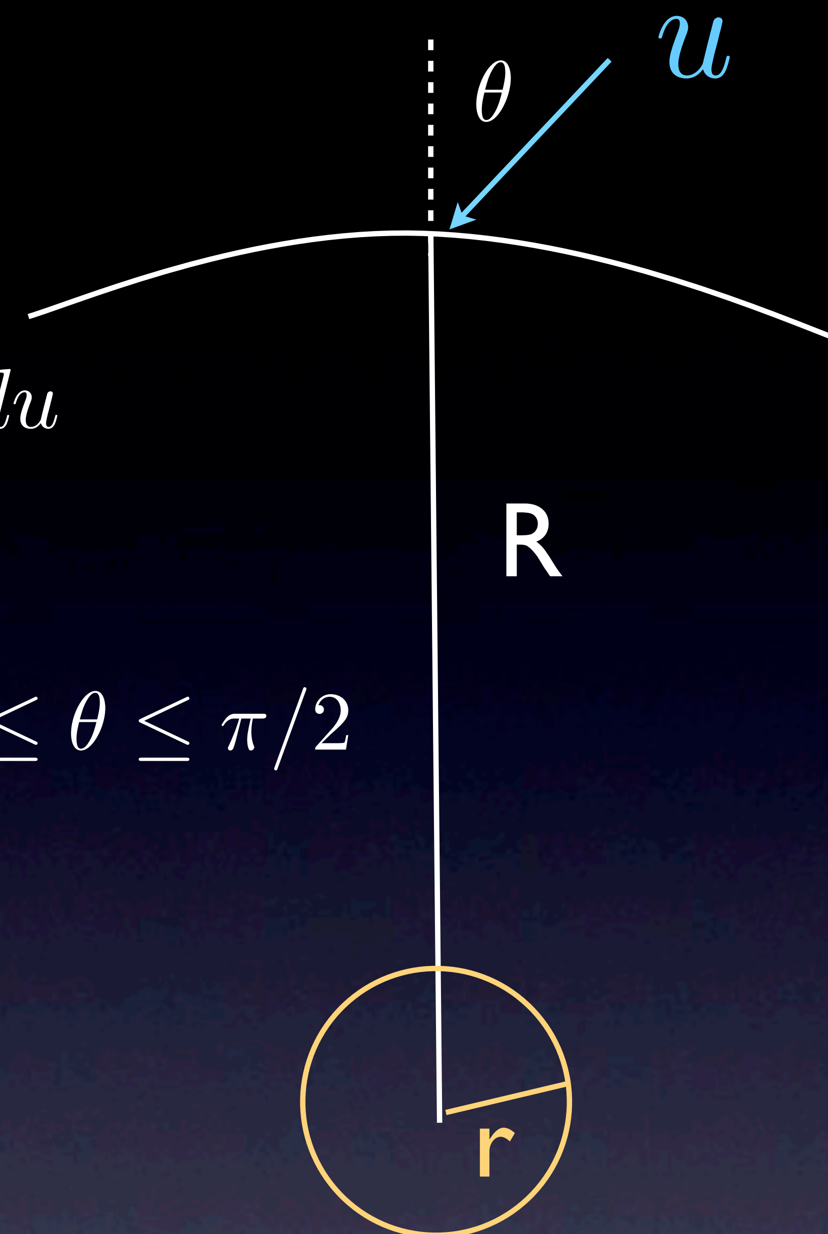
Spin-dependent interaction

$$\boxed{C^{\odot}_{\mathrm{SD}} \simeq 3.35\times 10^{20}\mathrm{s}^{-1}\left(\frac{\rho_{\mathrm{local}}}{0.3\mathrm{GeV/cm}^3}\right)\left(\frac{270\mathrm{km/s}}{v_{\mathrm{local}}}\right)^3\left(\frac{\sigma_{\mathrm{H,SD}}}{10^{-6}\mathrm{pb}}\right)\left(\frac{100\mathrm{GeV}}{m_{\mathrm{DM}}}\right)^2}$$

Spin-independent interaction

$$\boxed{\begin{aligned} C^{\odot}_{\mathrm{SD}} \quad &\simeq \quad 1.24\times 10^{20}\mathrm{s}^{-1}\left(\frac{\rho_{\mathrm{local}}}{0.3\mathrm{GeV/cm}^3}\right)\left(\frac{270\mathrm{km/s}}{v_{\mathrm{local}}}\right)^3\left(\frac{100\mathrm{GeV}}{m_{\mathrm{DM}}}\right)^2 \\ &\times\left(\frac{2.6\sigma_{\mathrm{H,SI}}+0.175\sigma_{\mathrm{He,SI}}}{10^{-6}\mathrm{pb}}\right)\end{aligned}}$$

Capture Rate



- velocity distribution at $R >> r$: f(u)
- Inward Flux : $$dF = \frac{1}{2} f(u) u \cos\theta d\cos\theta du = \frac{1}{4} f(u) u d\cos^2\theta du$$

$$0 \le \theta \le \pi/2$$

- Angular momentum per unit mass

$$J = Ru\sin\theta$$

$$dF = \frac{1}{4} f(u) udu \frac{dJ^2}{(Ru)^2}$$

- Velocity at r : $w = (u^2 + v^2)^{1/2}$

v : escape velocity $\Leftarrow \frac{1}{2}v^2 - \frac{GM}{r} = 0$

- Eq. of Motion $$\dot{r} = \sqrt{2(E-U) - \frac{J^2}{r^2}} = \sqrt{w^2 - \frac{J^2}{r^2}}$$

$$E = u^2/2 \qquad U = -GM/r = -v^2/2$$

Capture rate (2)

- $\Omega_v(w)$: rate per unit time at which a WIMP with velocity w will scatter to a velocity ≤ v
- (Flux that enters the shell with radius r) X (cature prob.)

$$4\pi R^2 \frac{1}{4} f(u) u du \int \frac{dJ^2}{(Ru)^2} \Omega_v(w) dt$$

$$= \quad 4\pi R^2 \frac{1}{4} f(u) u du \int \frac{dJ^2}{(Ru)^2} \Omega_v(w) \frac{2dr}{w} \frac{\theta(rw - J)}{(1 - J^2/(rw)^2)^{1/2}}$$

$$= \quad 4\pi r^2 dr \frac{f(u) du}{u} w \Omega_v(w)$$

- Capture rate per unit shell volume $\quad \frac{dC}{dV} = \int du \frac{f(u)}{u} w \Omega_v(w)$
- Scattering cross section σ (isotropic)
- Energy loss $\quad 0 \leq \frac{\Delta E}{E} \leq \frac{4 m_{\mathrm{DM}} M}{(m_{\mathrm{DM}} + M)^2}$

uniform distribution

M : mass of target nucleus

Capture rate (3)

- Scattering $w \;\rightarrow\; \leq v$ $\quad \dfrac{\Delta E}{E} > \dfrac{w^2 - v^2}{w^2} = \dfrac{u^2}{w^2}$

$$\Omega_v(w) = \sigma n w \frac{(m_{\rm DM}+M)^2}{4 m_{\rm DM} M}\left(\frac{4 m_{\rm DM} M}{(m_{\rm DM}+M)^2} - \frac{u^2}{w^2}\right)\theta\left(\frac{4 m_{\rm DM} M}{(m_{\rm DM}+M)^2} - \frac{u^2}{w^2}\right)$$

$$= \frac{\sigma n}{w}\left(v^2 - \frac{(m_{\rm DM}-M)^2}{4 m_{\rm DM} M}\right)\theta\left(v^2 - \frac{(m_{\rm DM}-M)^2}{4 m_{\rm DM} M}\right)$$

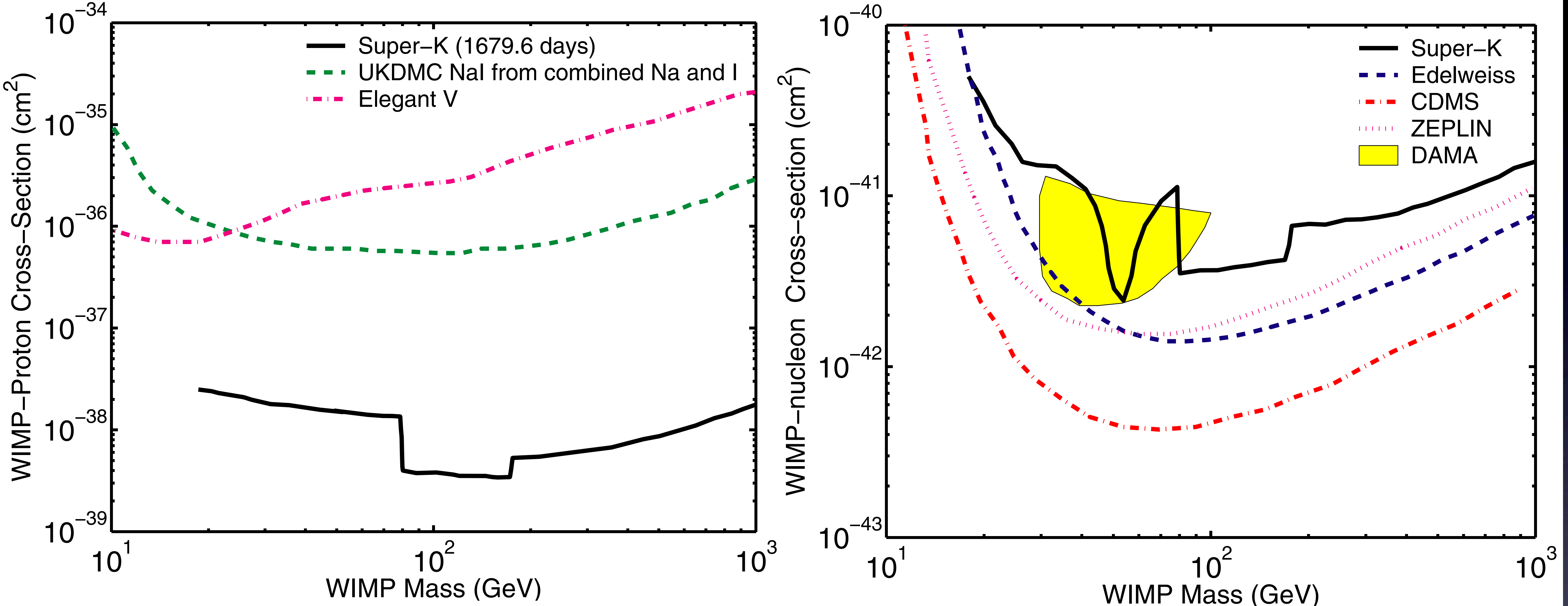
- Maxwell distribution for f(u)

$$f(u)du = n_{\rm DM}\left(\frac{3}{2\pi\bar{v}^2}\right)^{3/2}\exp\left(-\frac{3u^2}{2\bar{v}^2}\right)4\pi u^2 du$$

$$\boxed{\frac{dC}{dV} = \left(\frac{6}{\pi}\right)^{1/2}\sigma n n_{\rm DM}\bar{v}\frac{v^2}{\bar{v}^2}\left[1 - \frac{1-e^{-A}}{A}\right] \qquad A = \frac{3v^2}{2\bar{v}^2}\frac{4 m_{\rm DM} M}{(m_{\rm DM}-M)^2}}$$

$$\propto \sigma\bar{v}^{-1}(\rho/m_{\rm DM})A$$
$$\sim \sigma\bar{v}^{-3}\rho m_{\rm DM}^{-2}$$
$$(m_{\rm DM} \gg M)$$

Superkamiokande Limit



2009年11月10日火曜日

Positrons (and Anti-protons) from the Galactic Halo

- Positron (electron) Production

$$Q(E,\vec{r}) = \frac{1}{2}\left(\frac{\rho(\vec{r})}{m_{\mathrm{DM}}}\right)^2 \langle\sigma v\rangle \frac{dN^{e^+e^-}}{dE}$$

- Diffusion Equation (effect of galactic magnetic fields)

$$\boxed{\frac{\partial f_{e^\pm}(E,\vec{r})}{\partial t} = \underbrace{\boxed{K(E)\nabla^2 f_{e^\pm}(E,\vec{r})}}_{\text{diffusion (synchrotron motion in magnetic field)}} + \underbrace{\boxed{\frac{\partial}{\partial E}[b(e) f_{e^\pm}(E,\vec{r})]}}_{\text{energy loss by synchrotron and inverse Compton}} + \underbrace{\boxed{Q(E,\vec{r})}}_{\text{source}}}$$

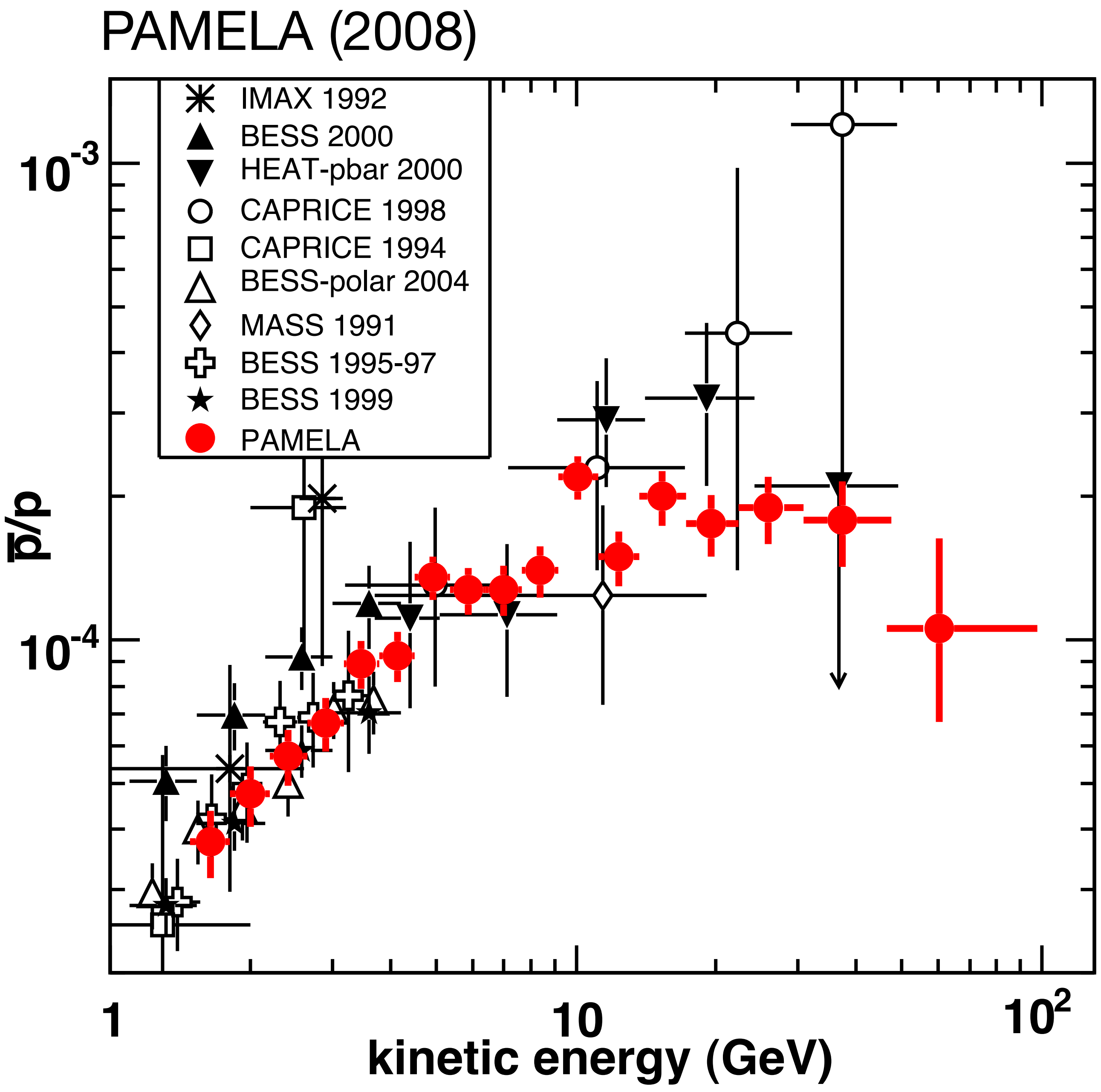
$$K(E) = K_0(E/\mathrm{GeV})^\delta \sim 3\times 10^{27}\mathrm{cm}^2\mathrm{s}^{-1}(E/\mathrm{GeV})^{0.6}$$

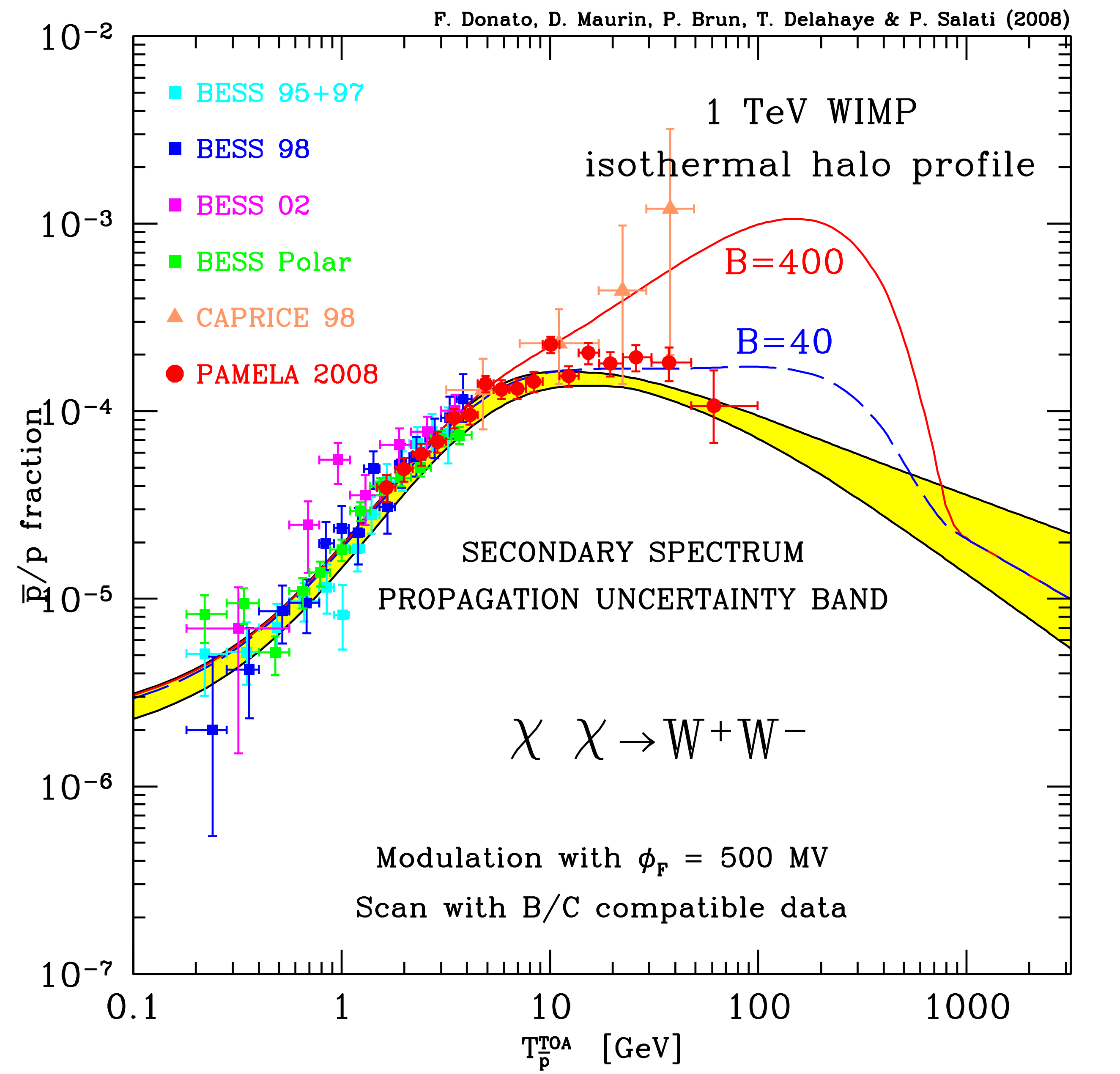
$$b(E) = 10^{-16}\mathrm{GeVs}^{-1}(E/\mathrm{GeV})^2 \qquad \Phi(E) = \frac{c}{4\pi} f_{e^\pm}(E,\vec{R}_\odot)$$

- Typical propagation length

$$\ell \sim \sqrt{K\Delta t} \sim \sqrt{KE/b} \sim (\text{a few kpc}) \times (E/\mathrm{GeV})^{-(1-\delta)/2}$$

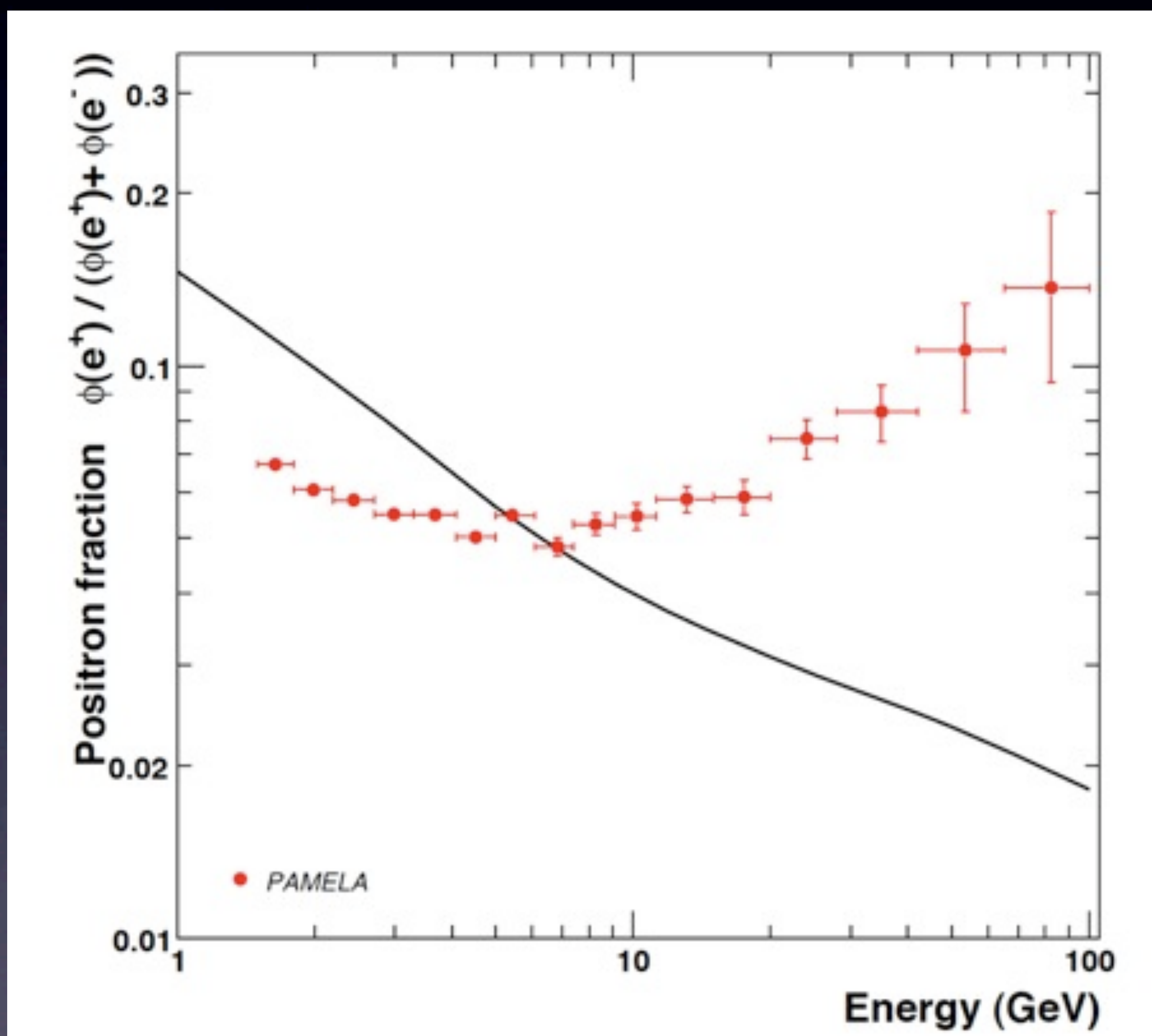
Anti-Proton Measurement



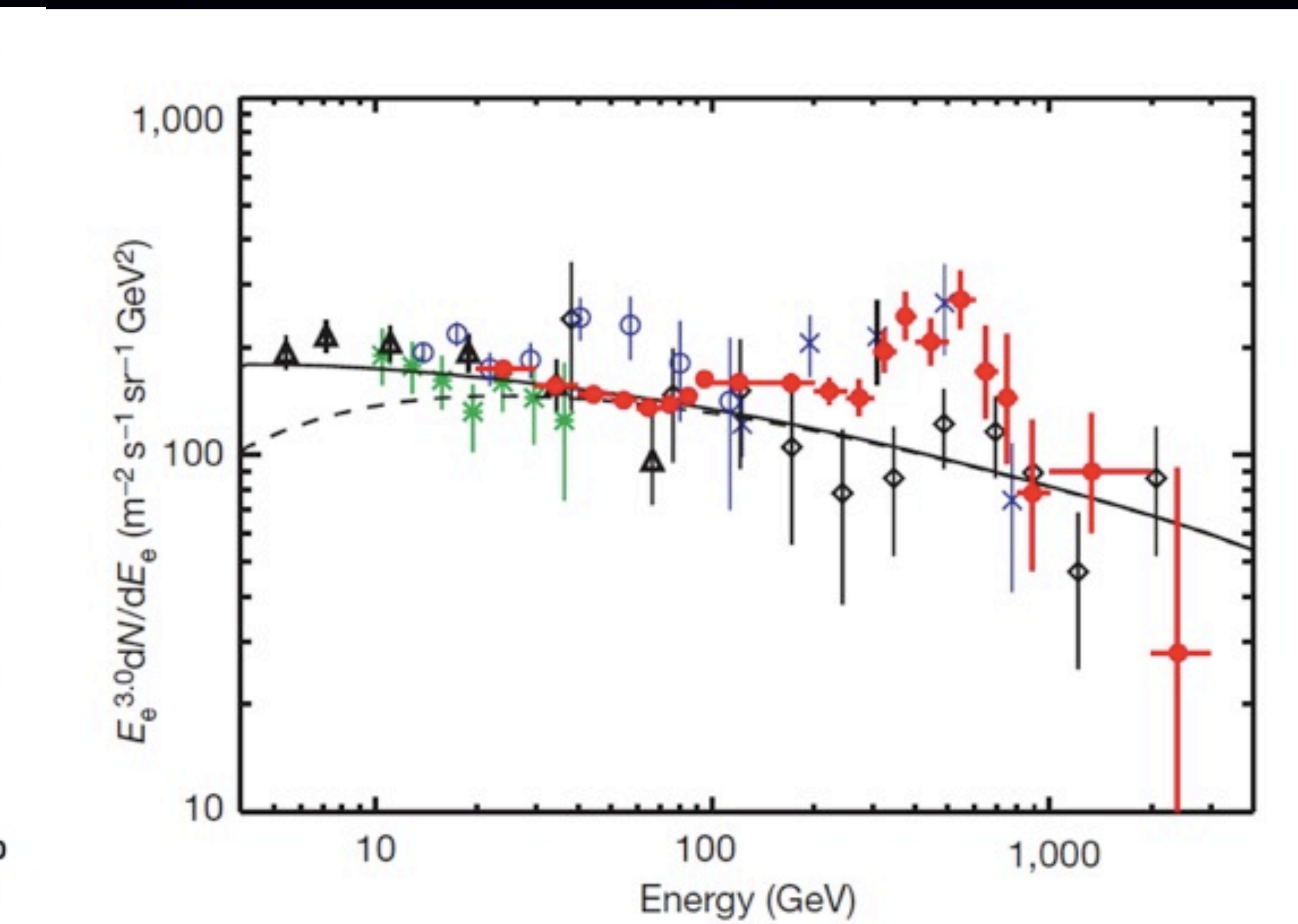


Recent Measurement of Cosmic Ray Electron/Positron Fluxes

PMELA arXiv:0810.4995



ATIC Nature 456 (2008)362



Signature of Dark Matter Annihilation/Decay ?

Dark Matter Annihilation/Decay

- PAMERA and ATIC/PPB-BETS results can be explained by annihilation of dark matter with mass ~1TeV and cross section

$$\boxed{\langle \sigma v \rangle \sim 10^{-23} \mathrm{cm}^{-3} \mathrm{s}^{-1}}$$

- This is much larger than expected from thermal relic

$$\langle \sigma v \rangle_{\mathrm{TH}} \sim 10^{-26} \mathrm{cm}^{-3} \mathrm{s}^{-1}$$

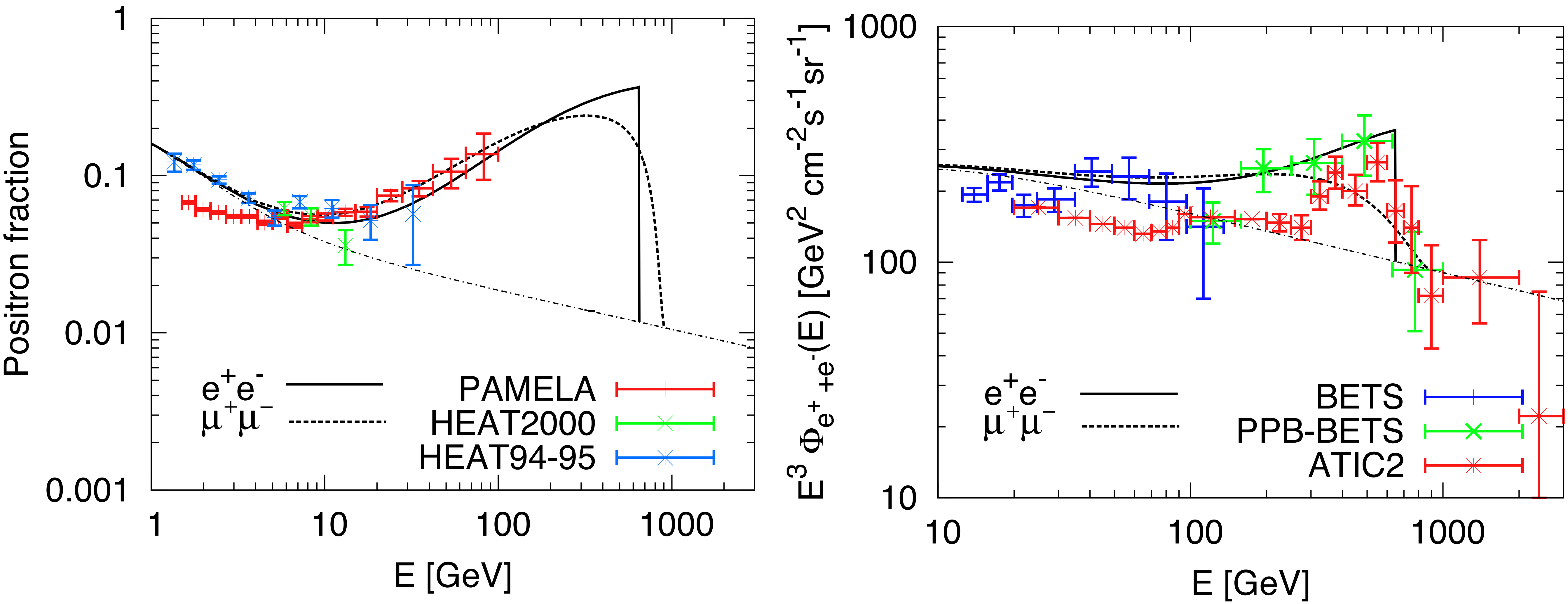
Non-thermal production?

- Decaying dark matter is a good candidate if it has lifetime

$$\boxed{\tau \sim 10^{26}\ \mathrm{s}}$$

- Annihilation/Decay into charged leptons is favored

Hisano et al (2009)

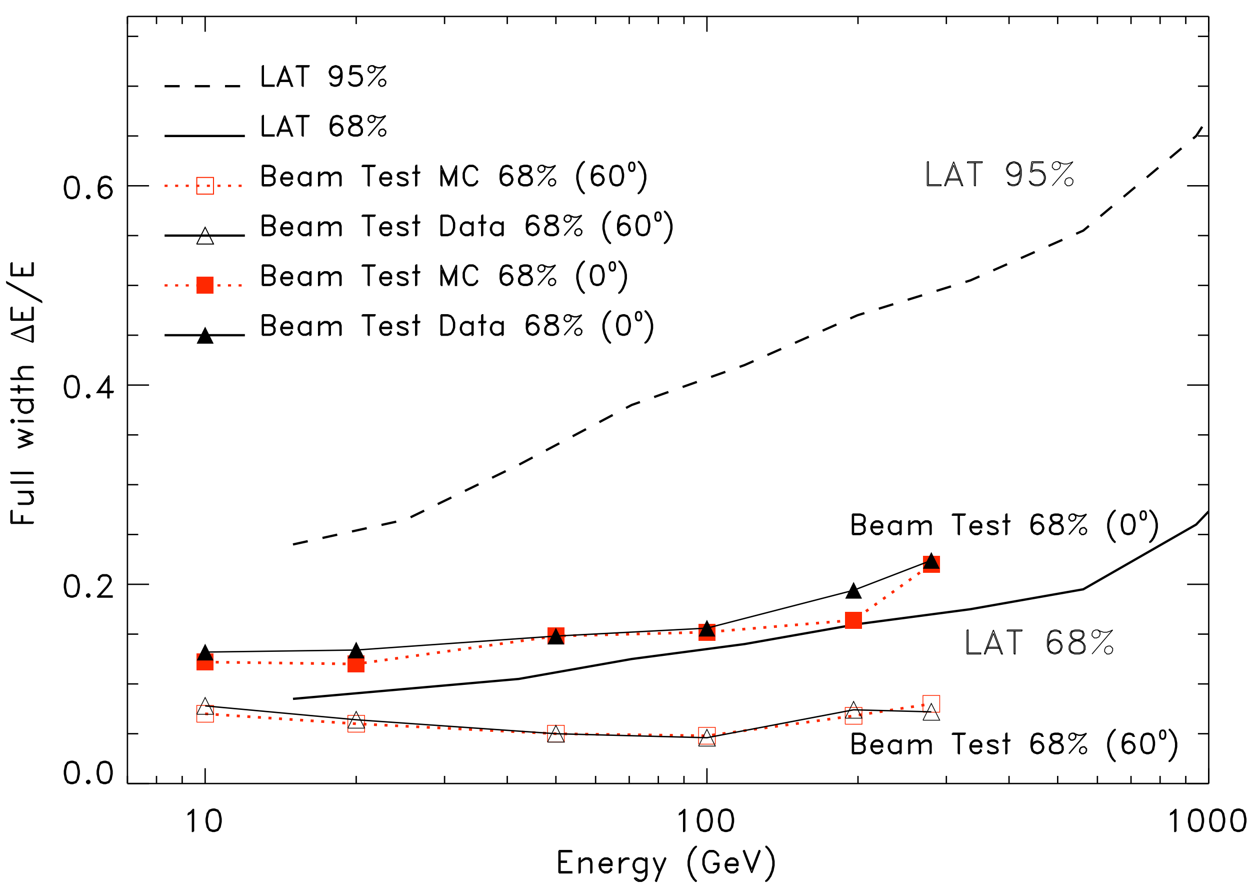


$$\langle \sigma v \rangle = 5 \times 10^{-24} \mathrm{cm}^{-3} \mathrm{s}^{-1}, \quad m = 650 \text{ GeV} \quad \text{for} \;\; e^{+}\, e^{-}$$

$$\langle \sigma v \rangle = 15 \times 10^{-24} \mathrm{cm}^{-3} \mathrm{s}^{-1}, \quad m = 900 \text{ GeV} \quad \text{for} \;\; \mu^{+}\, \mu^{-}$$

FERMI LAT

- Event selection and Energy reconstruction



IG. 1: (color online) Energy resolution for the LAT after ectron selection; the full widths of the smallest energy winow containing the 68% and the 95% of the energy dispersion istribution are shown. The comparison with beam test data p to 282 GeV and for on-axis and at 60° incidence shown n the figure indicates good agreement with the resolution stimated from the simulation.

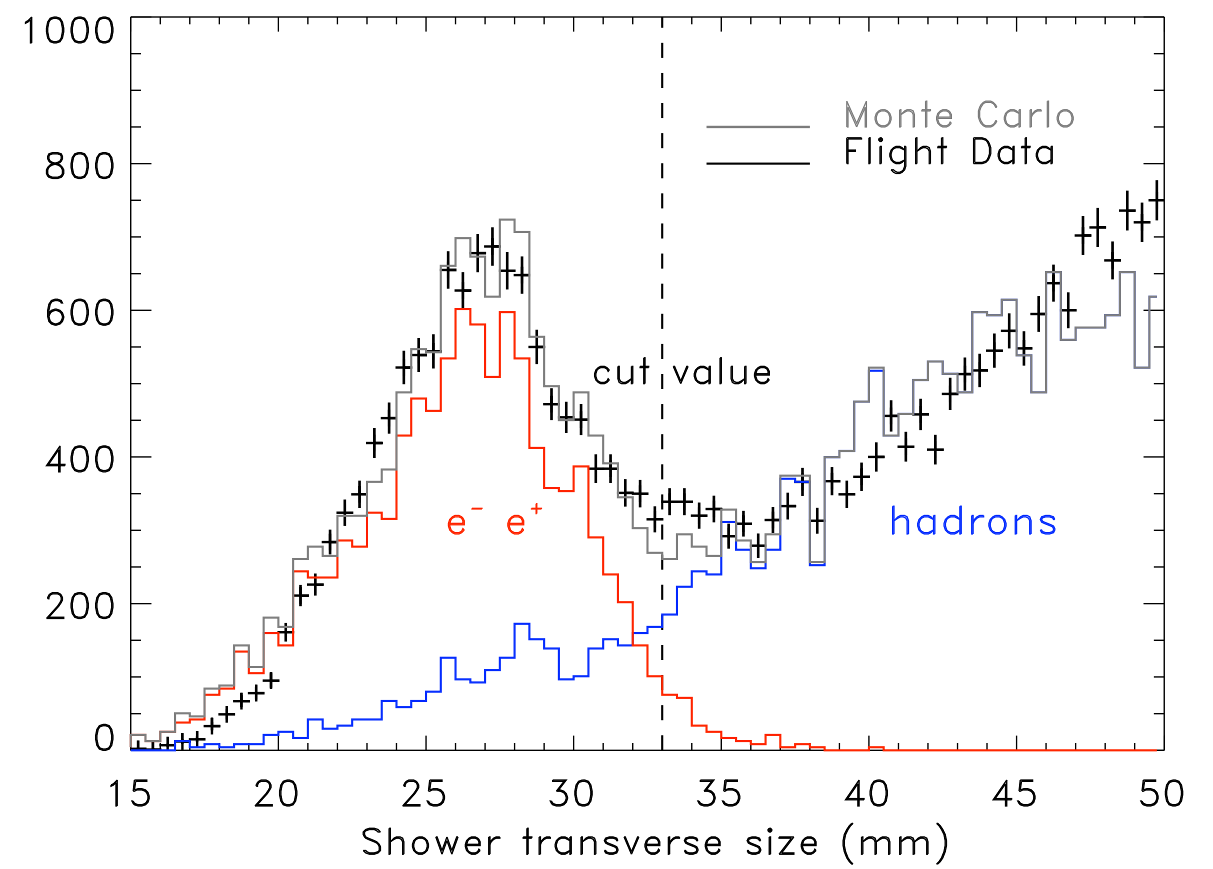
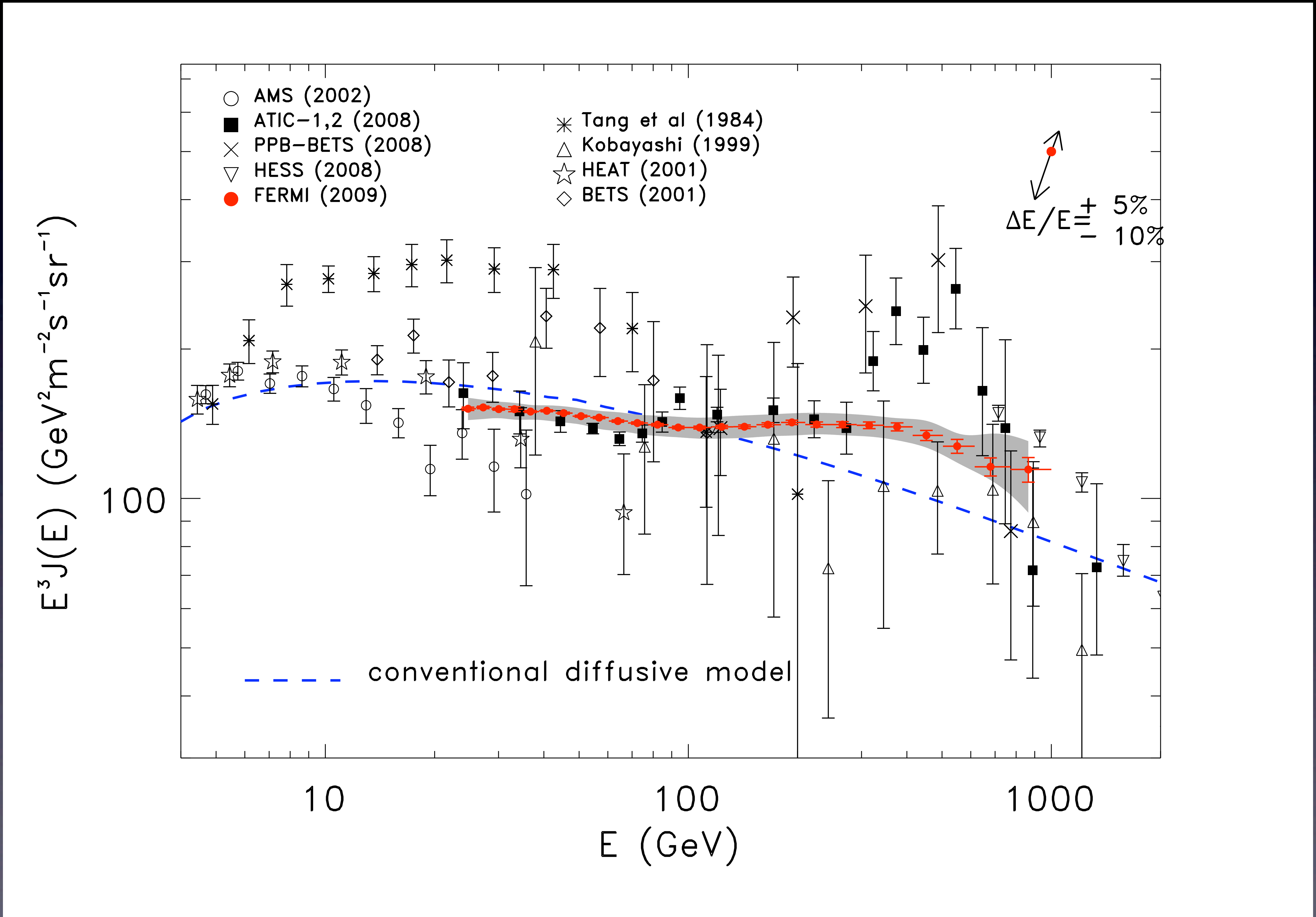


FIG. 2: (color online) Distribution of the transverse sizes of the showers (above 150 GeV) in the CAL at an intermediate stage of the selection, where a large contamination from protons is still visible. Flight data (black points) and MC (gray solid line) show very good agreement; the underlying distributions of electron and hadron samples are visible in the left (red) and the right (blue) peaks respectively.

Fermi LAT

- Electron Spectrum



Fermi LAT Result

- Data are well fit by a simple power low

$$J(E) \propto E^{-3.04} \quad (\chi^2 = 9.7 \text{ d.o.f } 24)$$

- The observation that the spectrum is much harder than the conventional one may be explained by assuming a harder electron spectrum at the source

- The significant flattering of the LA data above the model predictions for E > 70 GeV may also suggest the presence of one or more local sources of high energy CR electrons

$$J(E)_{\text{extra}} \propto E^{-\gamma_e} \exp(-E/E_{\text{cut}})$$

- The main purpose of adding such a component is to reconcile theoretical predictions with both the Fermi electron data and Pamela data

- Such an additional component also provides a natural explanation of the steepening of the spectrum above 1 TeV indicated by H.E.S.S

H.E.S.S.

- Electron measurement
  - γ ray background :

    |b| > 7°

    ➡ negligible γ ray contribution
  - hadronic background:

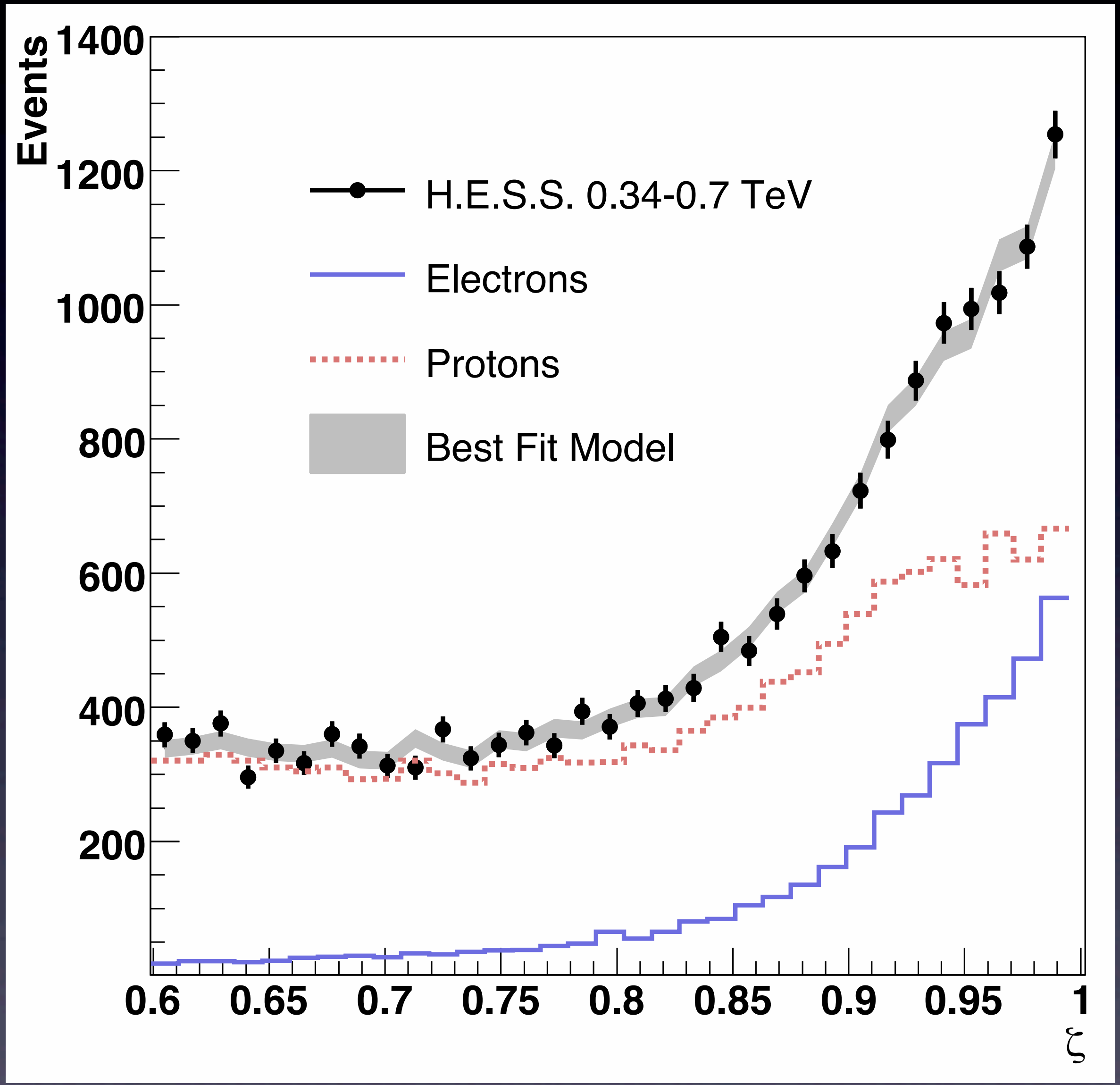
    electron likeness ζ

    ζ > 0.6

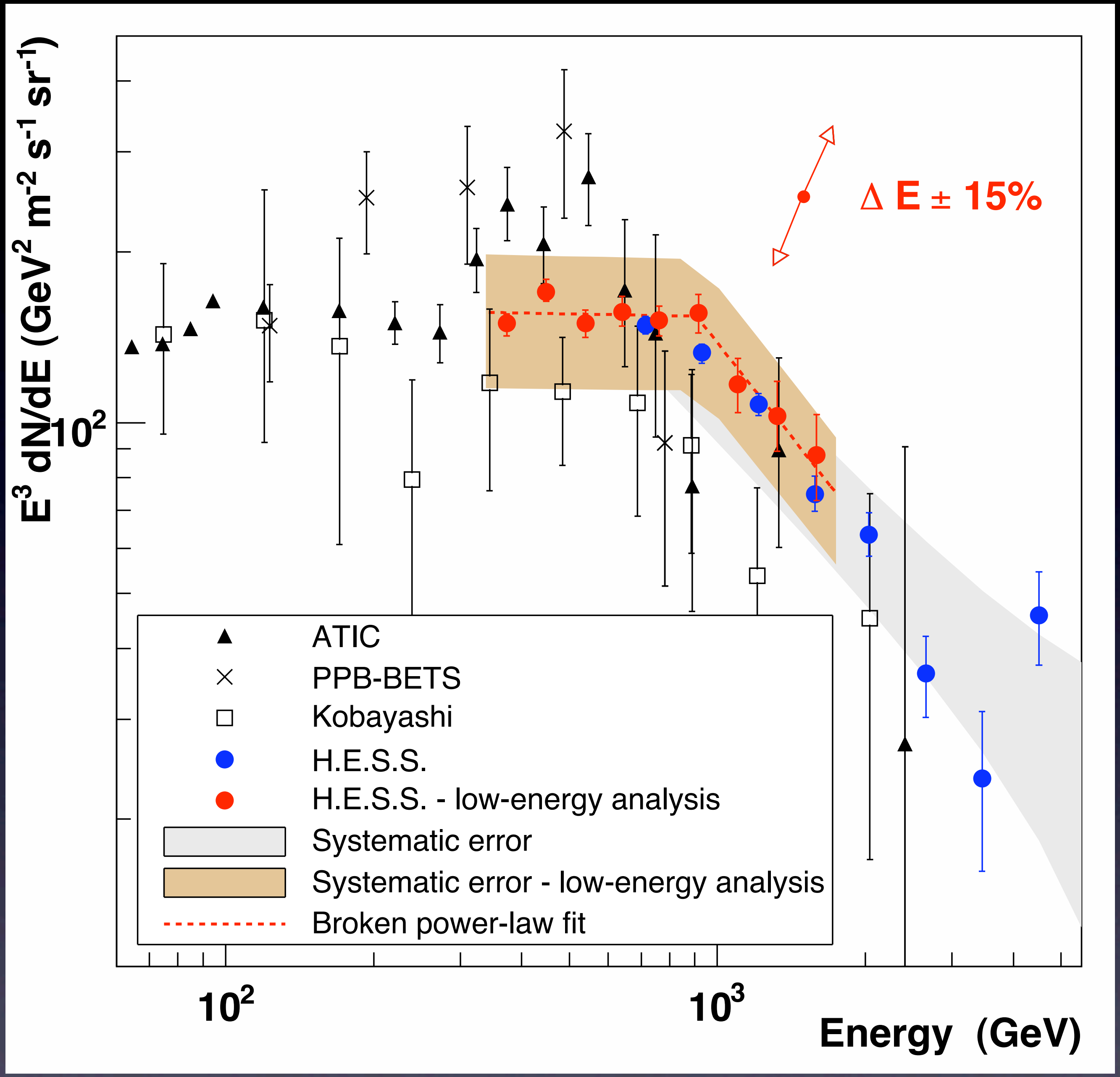
    ζ distribution simulation

    ➡ electron number density
  - Only data taken between 2004 and 2005

    mirror reflectivity degradation



H.E.S.S. Electron Spectrum



with H.E.S.S. starting at 340 GeV. The H.E.S.S. data with their lower statistical errors show no indication of a structure in the electron spectrum, but rather a power-law spectrum with spectral index of $3.0 \pm 0.1(\text{stat.}) \pm 0.3(\text{syst.})$ which steepens at about 1 TeV.

Propagation of Electrons in Galaxy

- Diffusion Equation

$$\frac{\partial f_{e^\pm}(E,\vec{r})}{\partial t} = \boxed{K(E)\nabla^2 f_{e^\pm}(E,\vec{r})} + \boxed{\frac{\partial}{\partial E}[b(e) f_{e^\pm}(E,\vec{r})]} + \boxed{Q(E,\vec{r})}$$

diffusion (synchrotron motion in magnetic field)

energy loss by synchrotron and inverse Compton

source

$$K(E) = K_0(E/\mathrm{GeV})^\delta \sim 3\times 10^{27}\mathrm{cm}^2\mathrm{s}^{-1}(E/\mathrm{GeV})^{0.6}$$

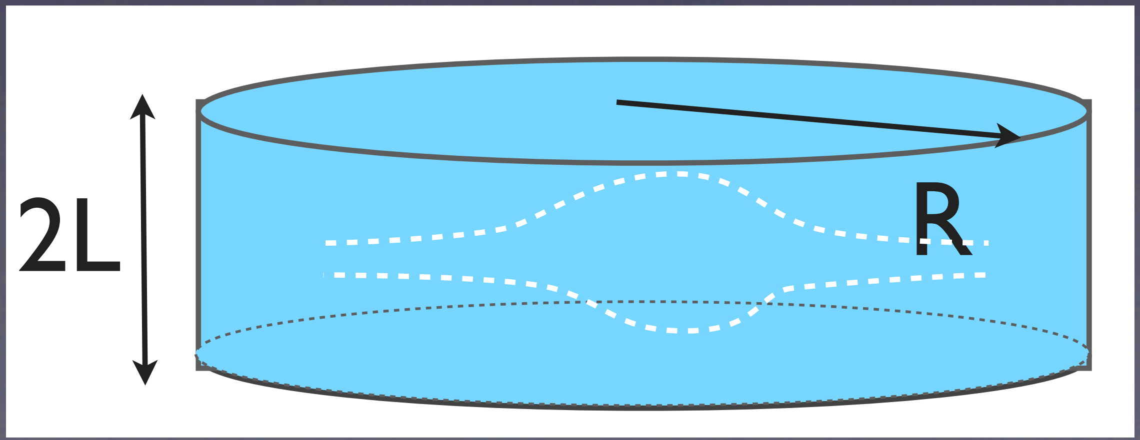
$$b(E) = 10^{-16}\mathrm{GeVs}^{-1}(E/\mathrm{GeV})^2$$

$$\Phi(E) = \frac{c}{4\pi} f_{e^\pm}(E,\vec{R}_\odot)$$

- Typical propagation length

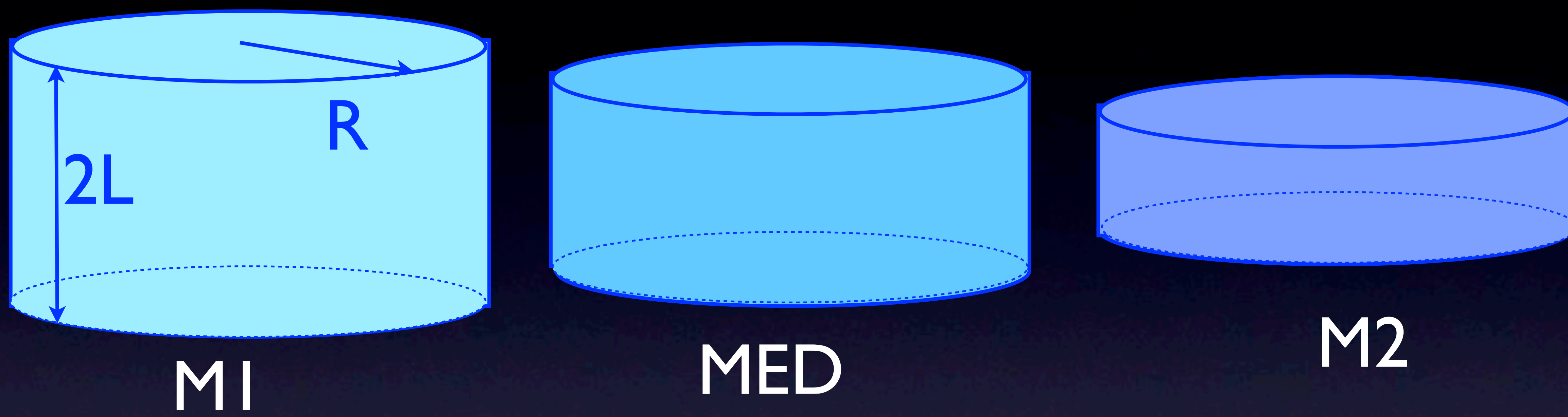
$$\ell \sim \sqrt{K\Delta t} \sim \sqrt{KE/b} \sim (\text{a few kpc}) \times (E/\mathrm{GeV})^{-(1-\delta)/2}$$

- Diffusion zone is approximated to be a cylinder



Three propergation models

- consistent B/C



	δ	$K_0(\mathrm{kpc}^2/\mathrm{Myr})$	$L(\mathrm{kpc})$	$R(\mathrm{kpc})$	
M1	0.46	0.0765	15	20	max electron flux
MED	0.70	0.0112	4	20	best fit to B/C
M2	0.55	0.0060	1	20	min electron flux

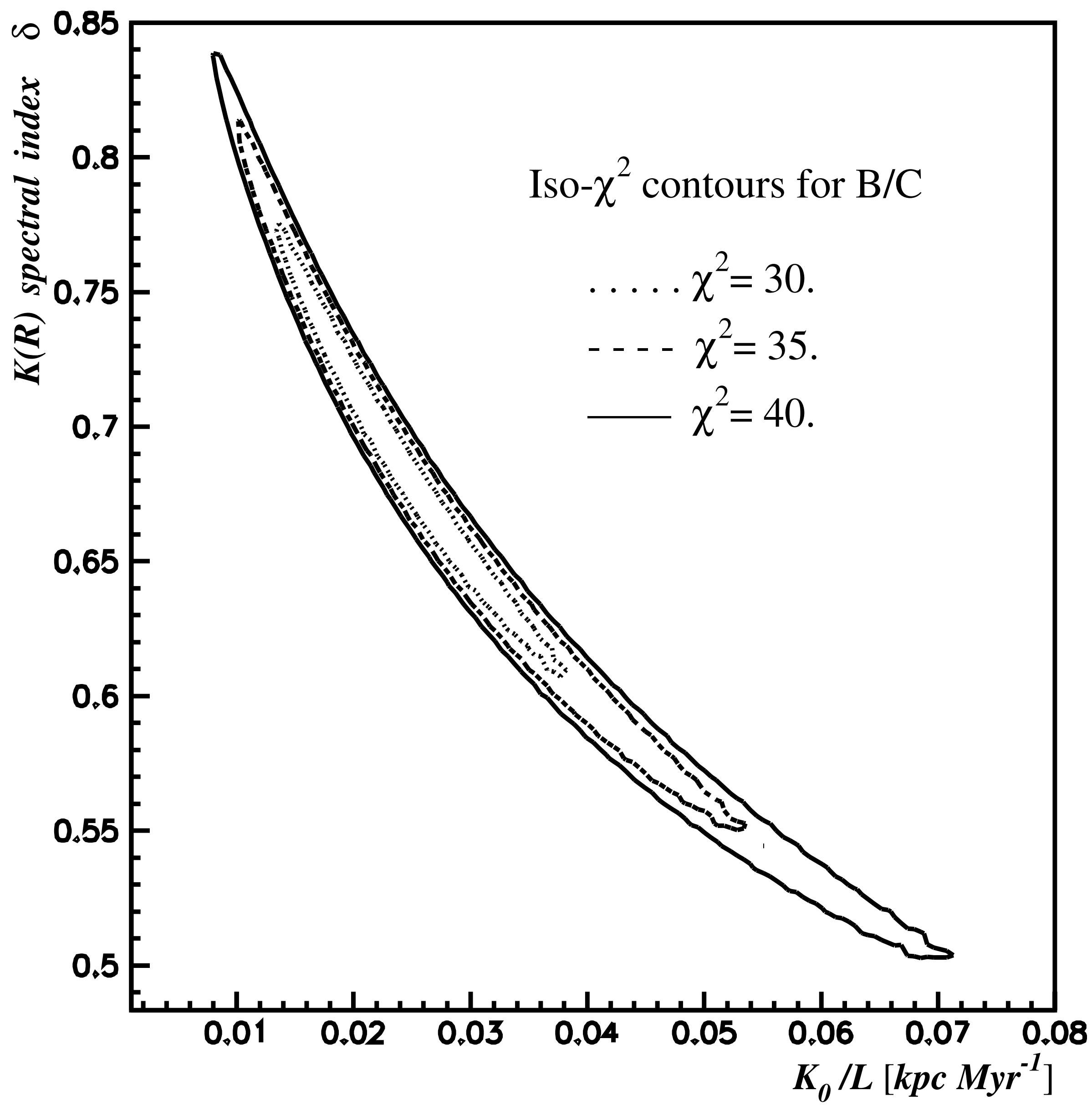
Delahaye et al PRD 77, 063527 (2008)

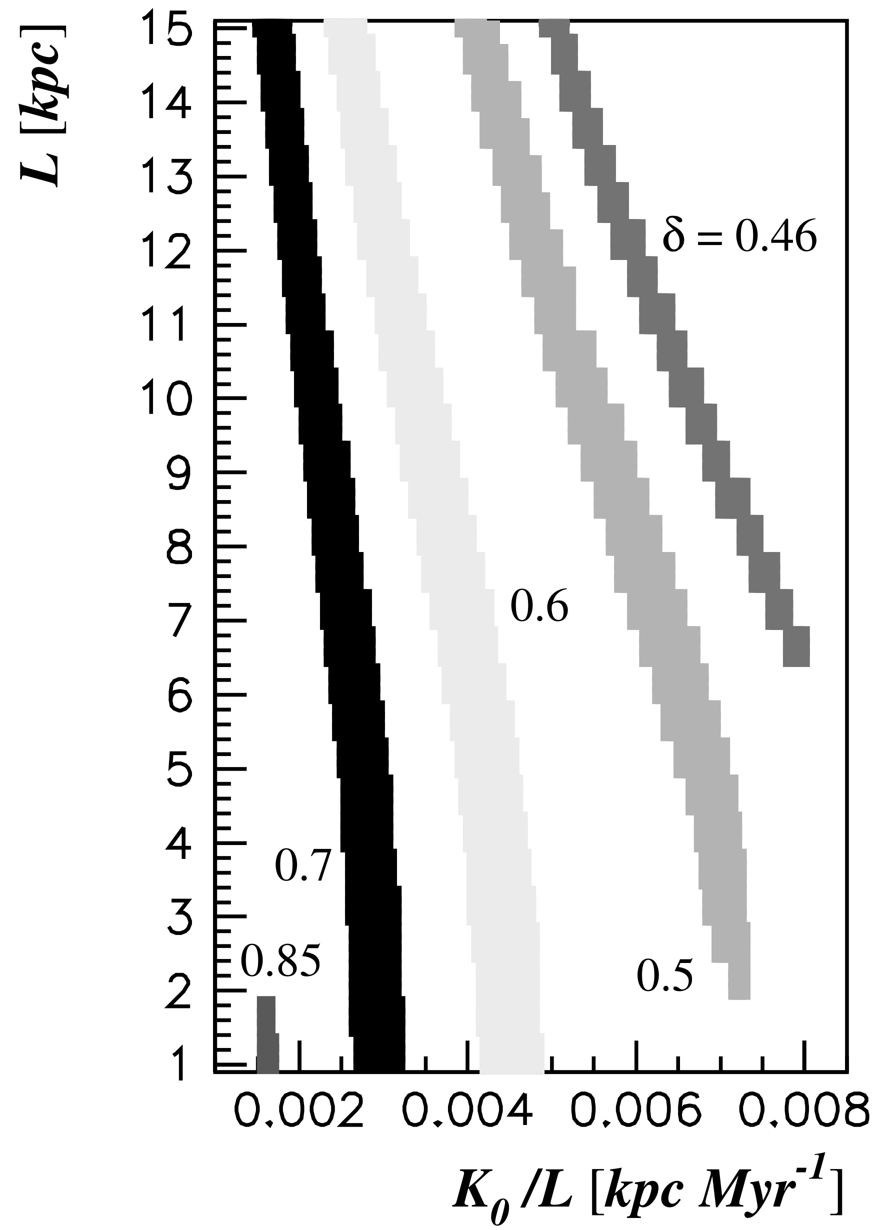
$$K(E) = K_0(E/\mathrm{GeV})^{\delta}$$

Constraint on propagation parameters

- B/C
  - B is purely secondary
  - C is primary
  - B/C is sensitive to the diffusion model parameters

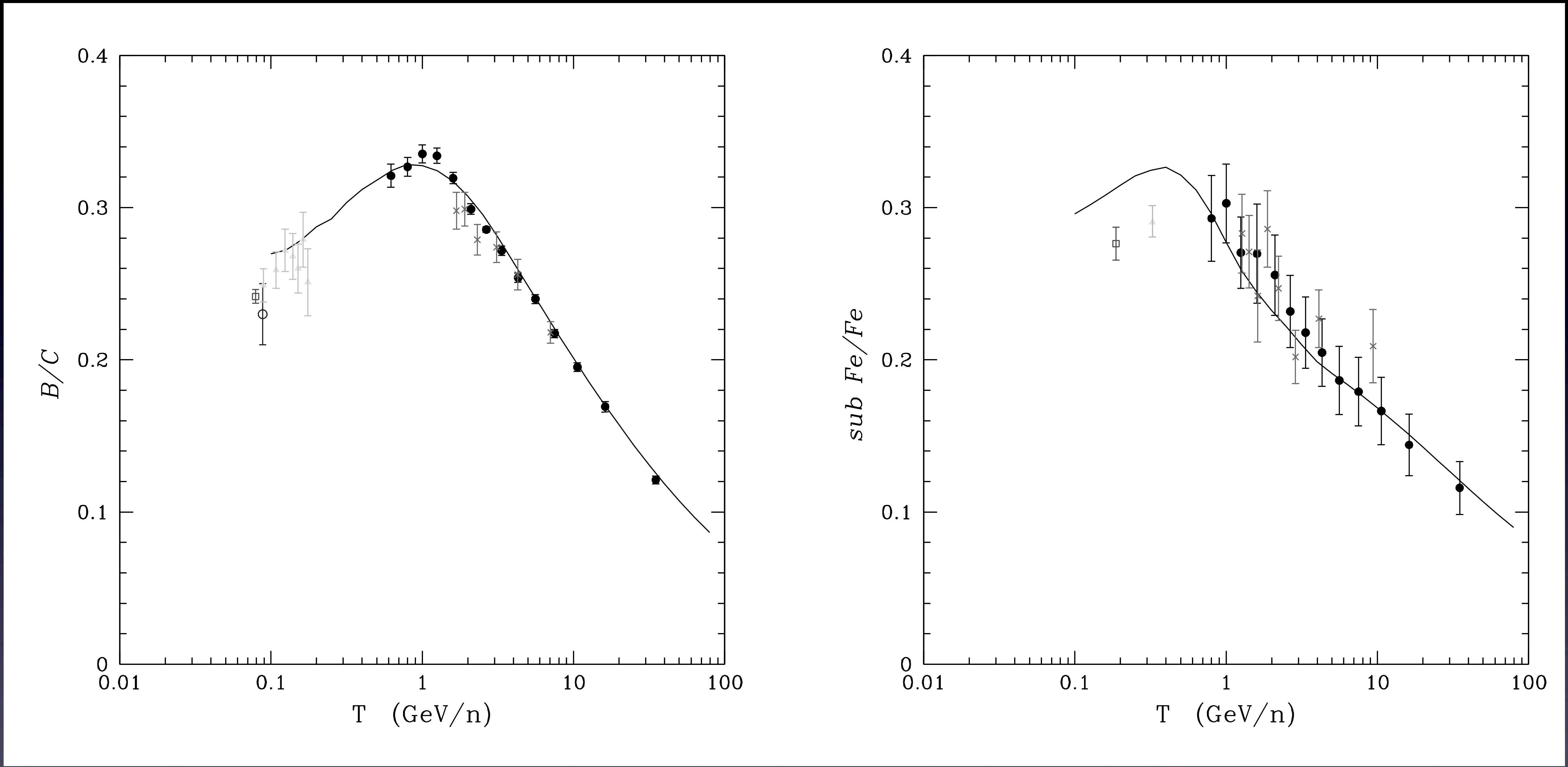
Maurin et al ApJ 555, 585 (2001)





B/C

Maurin et al ApJ 555, 585 (2001)



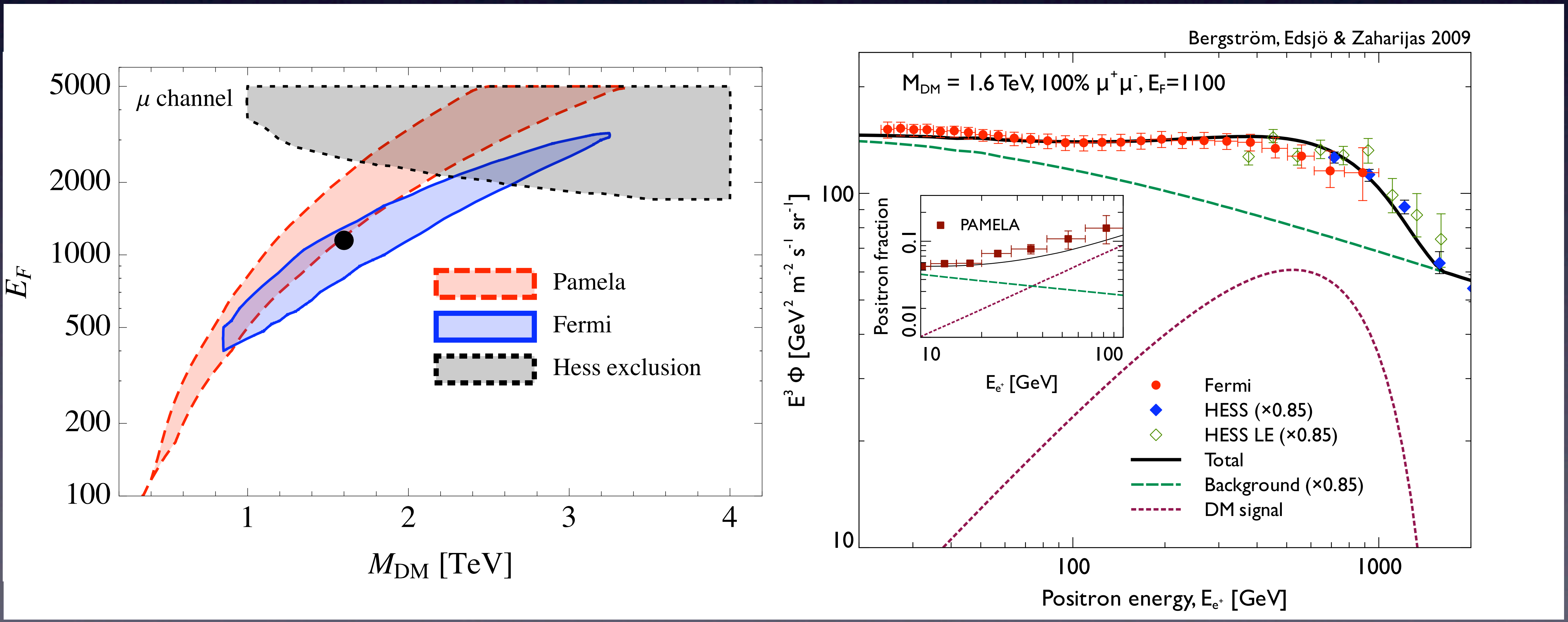
$$\mathrm{B/C} = \frac{{}^{10}\mathrm{B} + {}^{11}\mathrm{B}}{{}^{12}\mathrm{C} + {}^{13}\mathrm{C} + {}^{14}\mathrm{C}}$$

$$\text{sub Fe/Fe} = \frac{\mathrm{Sc} + \mathrm{Ti} + \mathrm{V}}{\mathrm{Fe}}$$

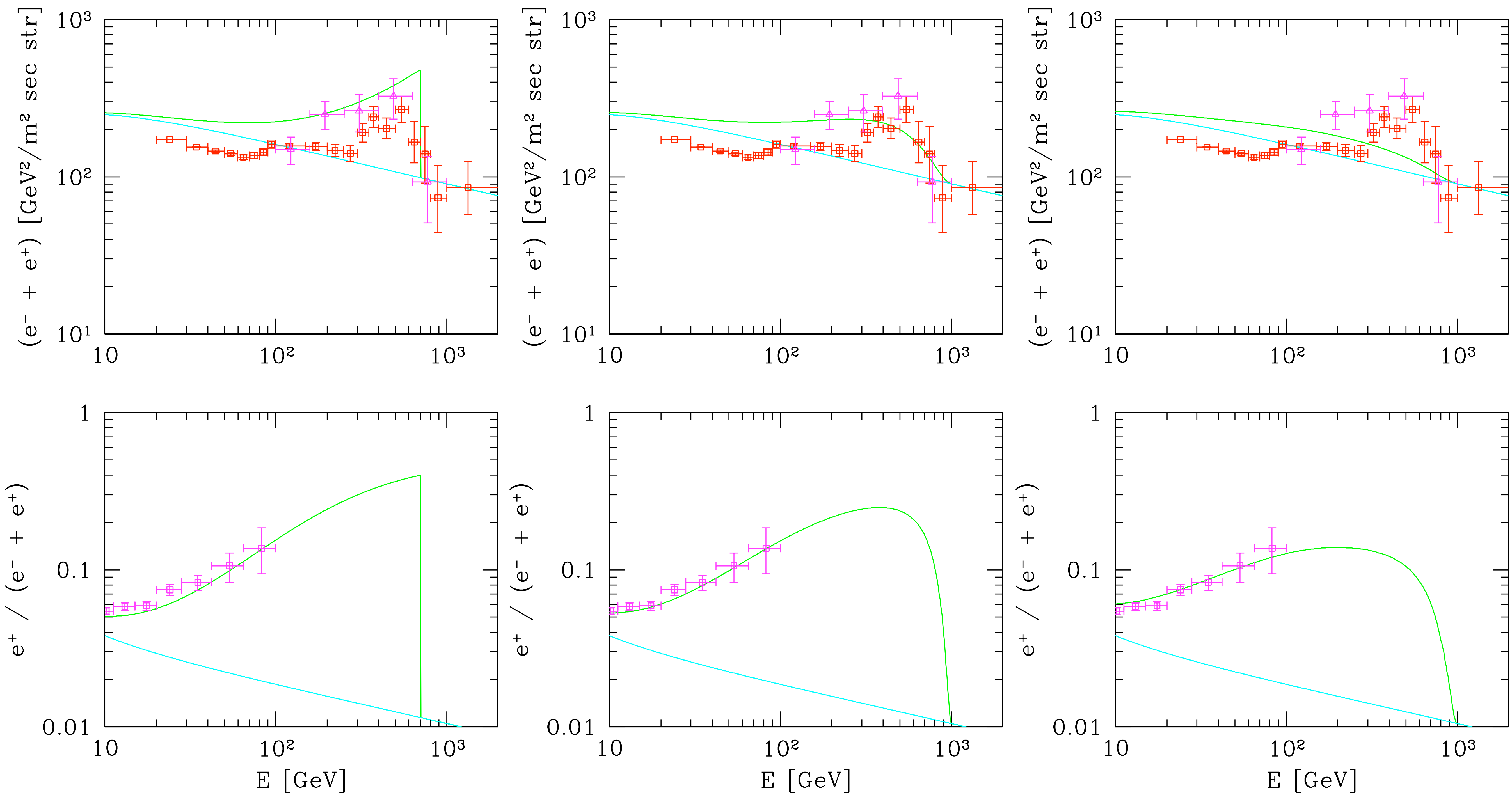
$$L = 9.5\mathrm{kpc} \quad K_0/L = 0.00345\mathrm{kpc\ Mpc}^{-1}$$

Dark matter interpretation of PAMERA, Fermi, H.E.S.S.

- “Bump” claimed by ATIC is not seen in Fermi
  - smaller boost factor (cross section)   B~1000
  - larger dark matter mass M = 1-4 TeV
  - annihilating predominantly into μ+ μ- is preferred



Bergstöm, Edsö, Zaharijas arXiv:0905.0333



e+e- 700GeV

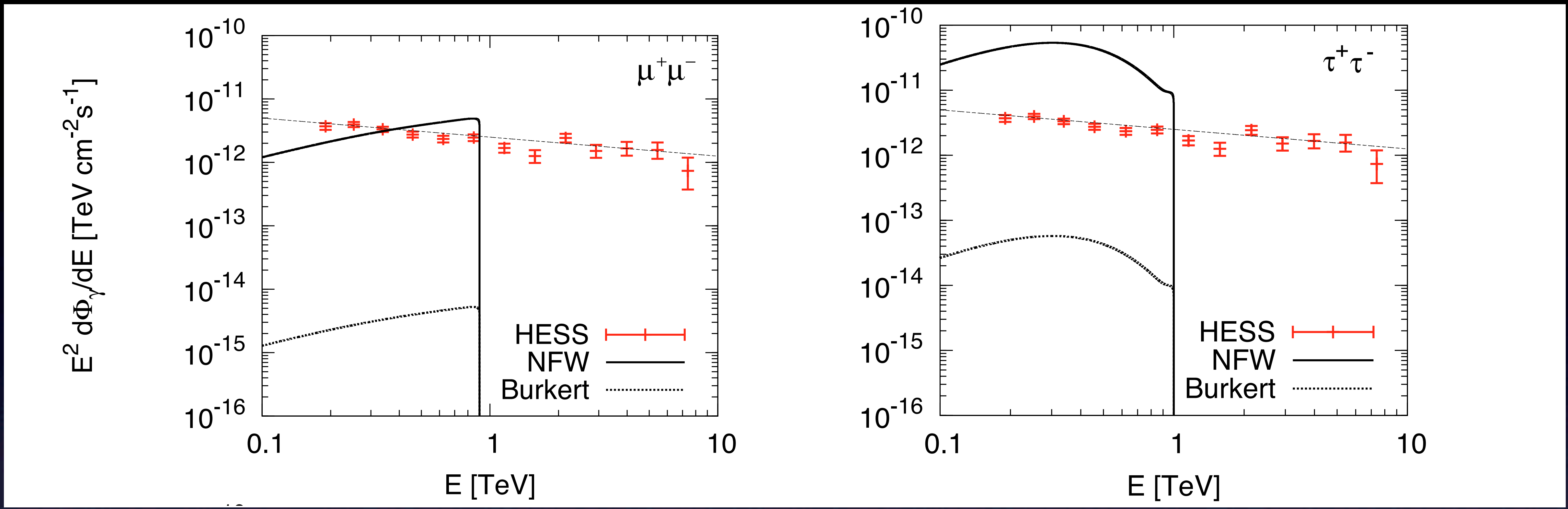
μ+μ- 1TeV

τ+τ- 1TeV

courtesy of Takeo Moroi

Gamma-ray

- Galactic center $\Delta\Omega < 10^{-5}$sr



- Diffuse (|b| > 10°)