ダークマターとCTA

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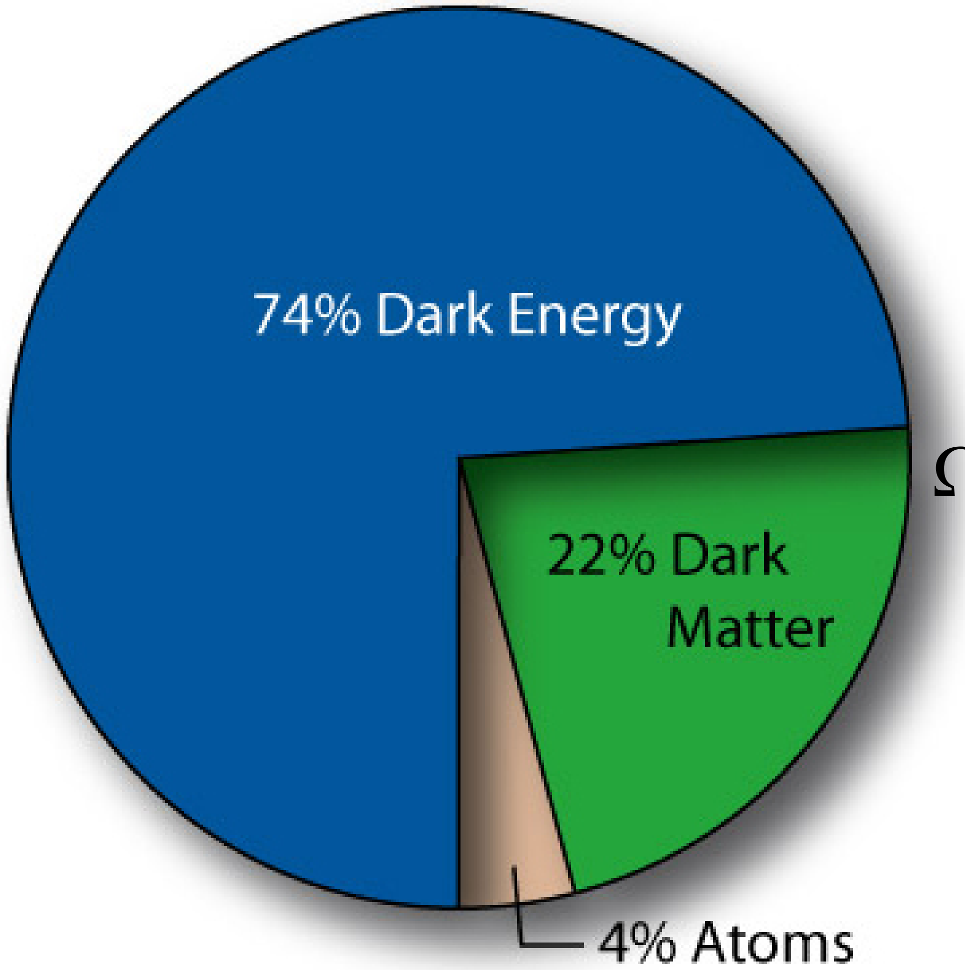
Dark Matter?



$$\Omega_i \equiv \left.\frac{\rho_i}{\rho_c}\right|_0$$

$$\Omega_{\mathrm{CDM}} h^2 \sim 0.1$$

http://map.gsfc.nasa.gov/media/060916

What is Dark Matter?

- It is massive ($\rho \propto a^{-3}$)
- It is stable ($\tau >> 10^{18}$ sec)
- It does not scatter off photons so much
  (Is it a bound-state?)
- It is neutral
  (from experiments of sea water $m<10^6$ GeV)
- The velocity dispersion is small [cold dark matter (CDM)]

Candidate of particle (cold) dark matter

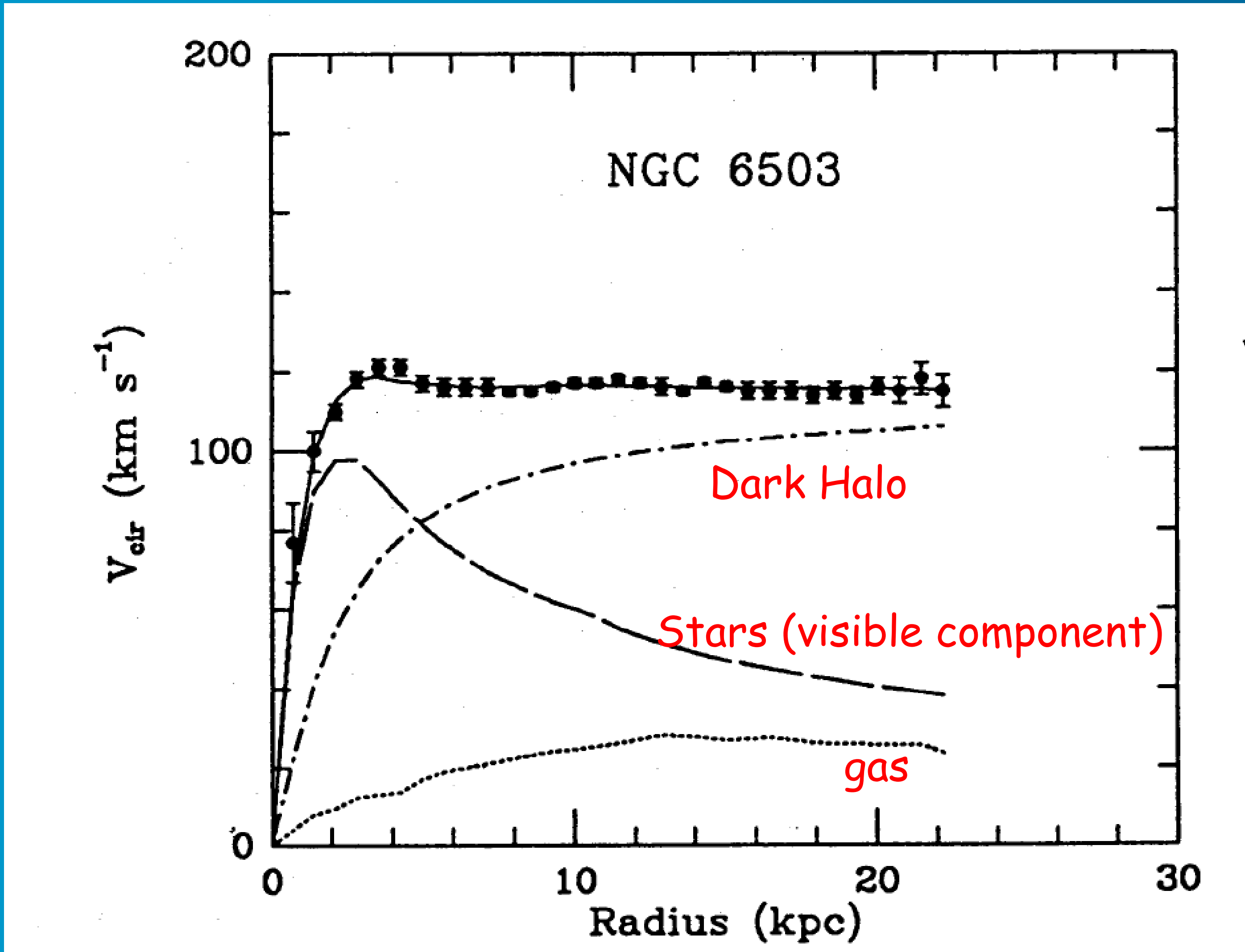
- Stable or long-lived new particle
  - Neutralino
  - Gravitino
  - Right-handed sneutrino
  - Axino
  - …

- Oscillating scalar field
  - Axion
  - Moduli
  - …

Another candidates

- Primordial black hole
- Brown dwarf
- WIMPZILLA
- Integral constant in Horava-Lifshitz gravity
- Quark nugget (strange-quark matter)
- Solutions in (relativistic-) Modified Newtonian Dynamics (MOND)
- …

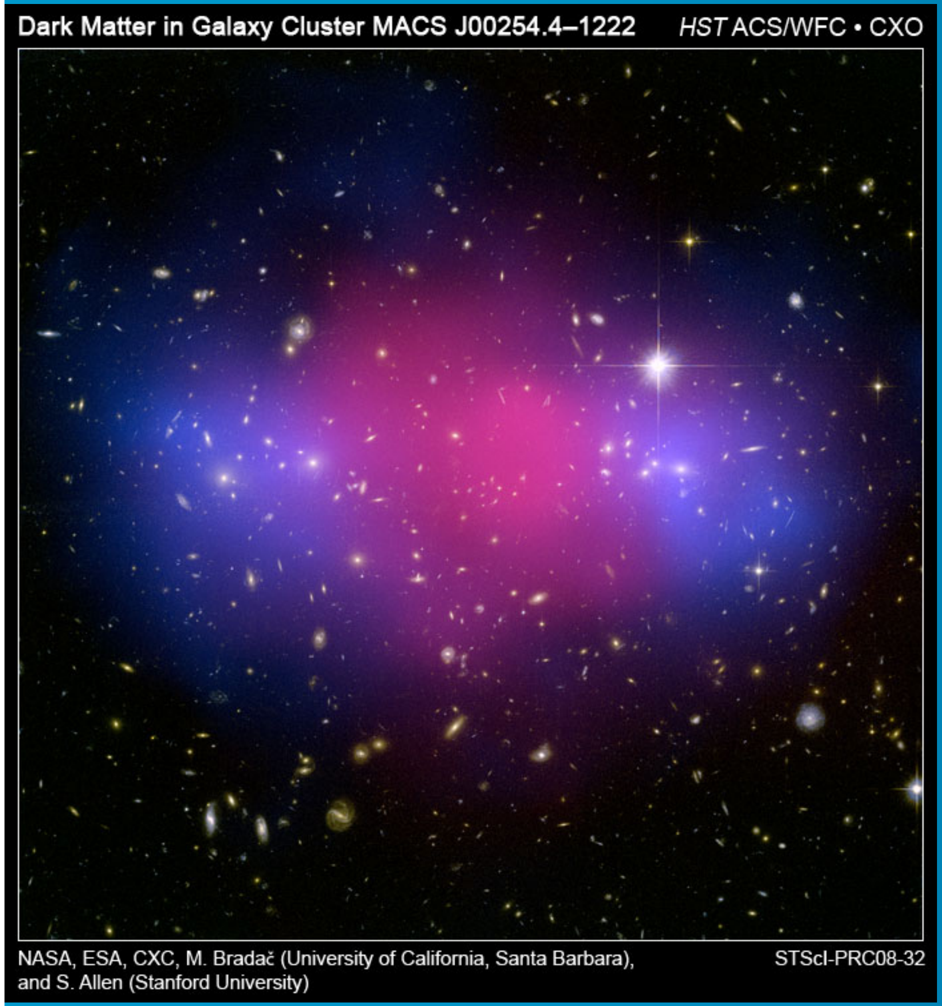
Rotation curve



$M(r) \propto r$

Begeman, Broils,Sandars etal (91)

Gravitational lens in colliding cluster of galaxies

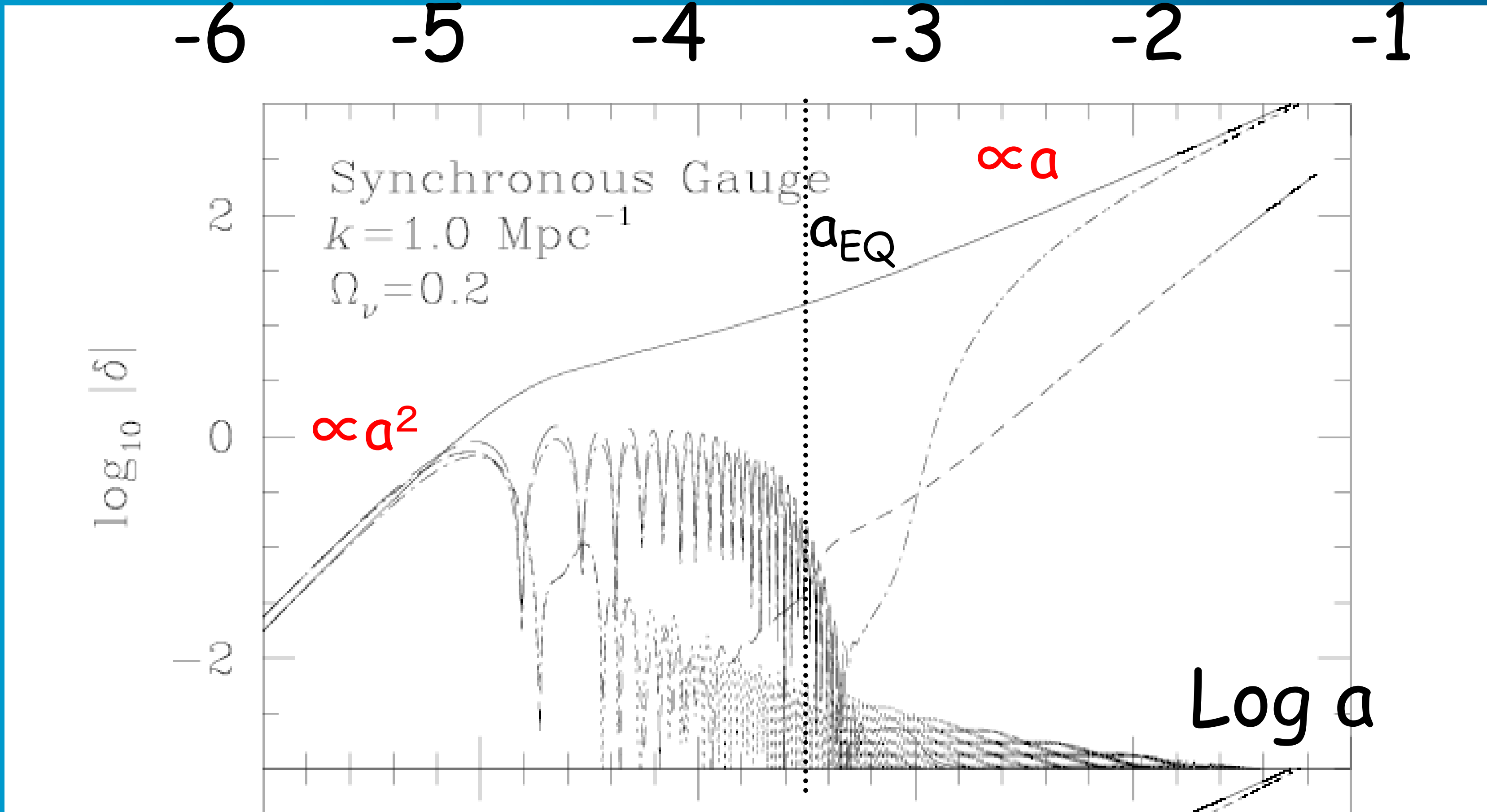


(2007)

- Red: Baryon observed by X-ray produced by brems of thermal electron
- Blue: DM observed by gravitational lens

Time-evolution of fluctuation III

(II) Horizon reentry before matter-radiation equality epoch



Ma and Bertschinger (95)

See also 松原隆彦「シリーズ　現代の天文学3　宇宙論 II　宇宙の進化」

Cluster baryon fraction

- Cluster can have a representative distribution in the Universe of both baryon and DM

$$f_{\rm b} = \frac{\Omega_{\rm b}}{\Omega_{\rm m}} \simeq f_{\rm gas} + f_{\rm gal}$$

- $\Omega_b h^2$ is independently known, f_{gas} was observed by X-ray from Oxygen

$$\Omega_{\rm m} = \frac{\Omega_{\rm b}}{f_{\rm gas} + f_{\rm gal}} \simeq \frac{\Omega_{\rm b}}{0.08h^{-1.5} + 0.01h^{-1}}$$

$\Omega_m \sim 0.2$

Combined Figure

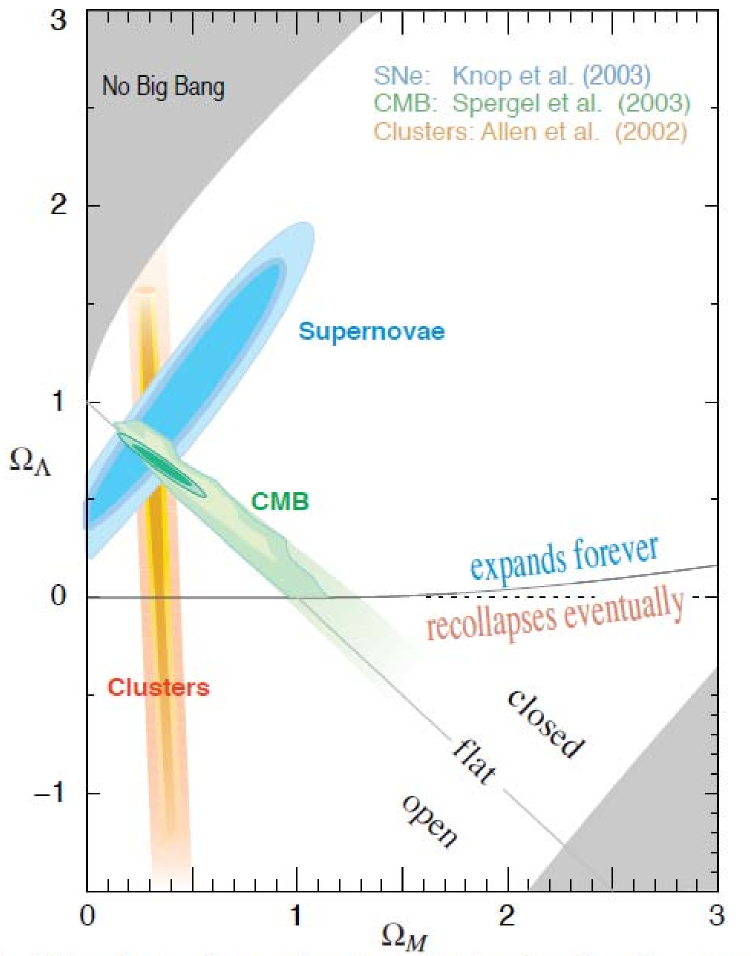
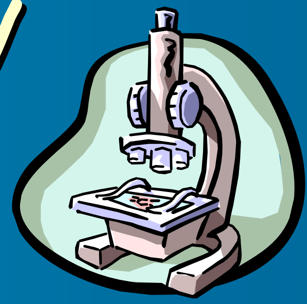


Figure 21.1: This shows the preferred region in the Ω_m–Ω_Λ plane from the compilation of supernovae data in Ref. 18, and also the complementary results coming from some other observations. [Courtesy of the Supernova Cosmology Project.]

Riess et al (98), Lahav-Liddle PDG (09)

Introduction to SUSY



- Supersymmetry (SUSY)
  - Solving "Hierarchy Problem"
  - Realizing "Coupling constant unification in GUT"

Fermion	⟷	Boson
quark	⟷	squark
lepton	⟷	slepton
photino	⟷	photon
gravitino	⟷	graviton

neutralino ← photino

Depending on SUGRA models

Hierarchy Problems

- GUT-scale

$$M_X \approx 10^{14} - 10^{15} GeV$$

- Weak-scale

$$M_W \approx 10^{2} - 10^{3} GeV$$

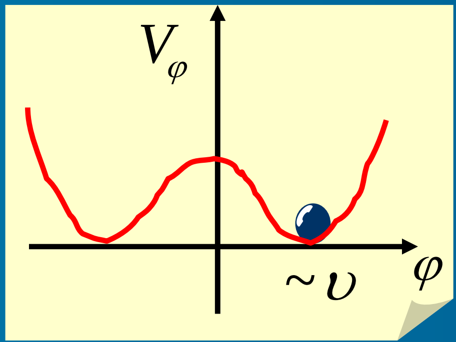
12-13 orders of magnitude !!!

Higgs mass

$$m_{\varphi 0}^2 = \frac{d^2 V_\varphi}{d\varphi^2} \approx \lambda \upsilon^2 \approx O(M_W^2)$$

where Higgs's potential

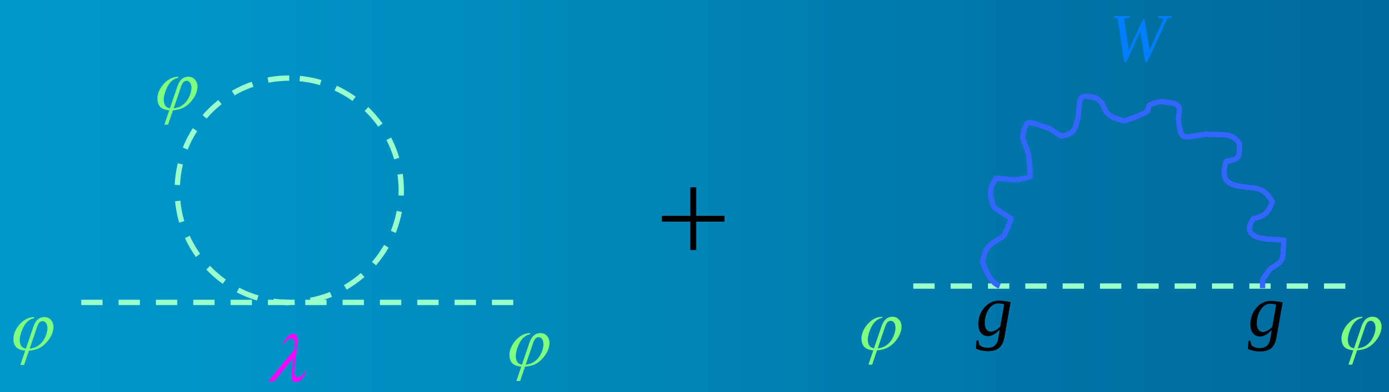
$$V_\varphi = \lambda\left(\varphi^\dagger \varphi - \upsilon^2/2\right)^2$$



c.f) Masses of fermions and vector bosons

$$m_\psi \sim h_\psi \langle \varphi \rangle,\ m_Z \sim g \langle \varphi \rangle$$

Radiative correction to Higgs mass in Quantum Field Theory



$$\delta m_\varphi^2 \sim \lambda \Lambda^2 + g^2 \Lambda^2$$ ⬅ Quadratic divergence

Cut off scale $\Lambda \sim M_X \sim 10^{15}$ GeV

$$\delta m_\varphi^2 \sim \left(10^{15}\ \text{GeV}\right)^2 \ ?$$

How can we resolve the problem?

Weak scale in the tree level, $m_{\varphi 0}^2 \sim (10^2 GeV)^2$

In total, $\delta m_\varphi^2 \sim (10^{15} GeV)^2$

$$m_\varphi^2 \sim m_{\varphi\ 0}^2 + \delta m_\varphi^2 \sim (10^{15} GeV)^2 ?$$

To retain the hierarchy, we require an accidental cancellation,

$$m_{\varphi\ 0}^2 + \delta m_{\varphi\ 1}^2 + \delta m_{\varphi\ 2}^2 + \delta m_{\varphi 3}^2 + \ldots \sim (10^2 GeV)^2 ?$$

$\left[O(10^{15} GeV)\right]^2$

GDP in USA (2002)?

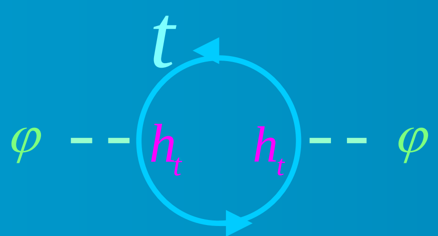
$ 10,110,087,734,958.95
-) $ 10,110,087,734,957.70

$ 1.25

Fine tuning!

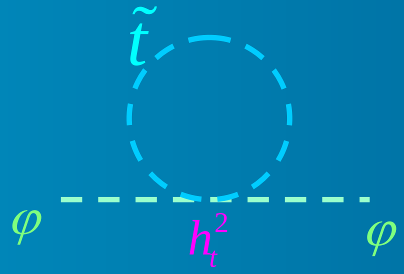
Solution in SUSY

In exact SUSY, the quadratic divergence is canceled by both boson and fermion loops.



$$-\frac{1}{(4\pi)^2}h_t^2\Lambda^2$$

+



$$\frac{1}{(4\pi)^2}h_t^2\Lambda^2$$

$= 0$

Exact SUSY

Even if ~~SUSY~~,

$$\delta m_\varphi^2 \sim \frac{1}{(4\pi)^2} h_t^2 m_{\tilde{t}}^2 \ln\left(\frac{\Lambda^2}{m_{\tilde{t}}^2}\right)$$

We don't need a fine tuning when

$$m_{\tilde{t}}^2 \sim m_{\tilde{b}}^2 \sim \ldots \sim O(M_W^2)$$

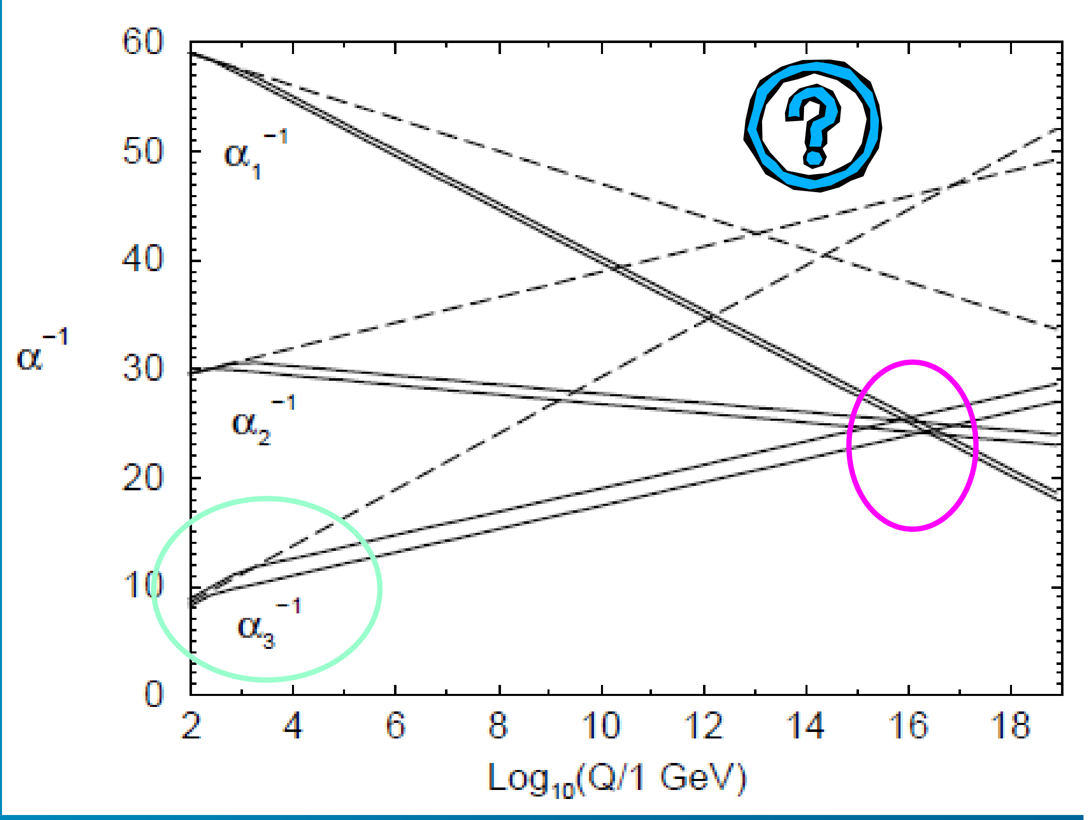
SUSY GUT

The coupling constants are unified at

$$M_X \approx 10^{16} GeV$$

A lot of new particles ,which do not obey the asymptotic free, appear at

$$\mu \geq 10^2 GeV$$



Martin, "A Supersymmetry Primer"

Lightest SUSY particle (LSP)

- R-parity conservation

  i)Decay

$$\tilde{\tau} \rightarrow \chi + \tau$$

(-1) (-1) (+1)

  ii) Pair annihilation/production

$$f + \overline{f} \leftrightarrow \chi + \chi$$

(+1) (+1) (-1) (-1)

Thermal freezeout

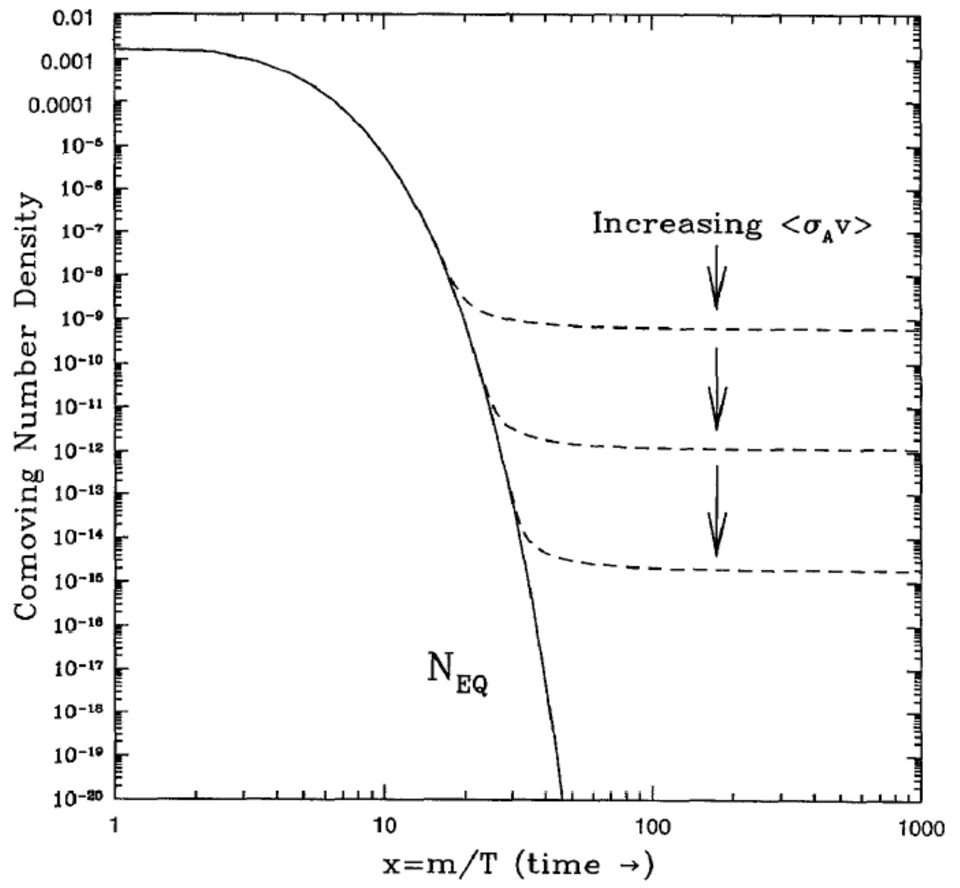
Boltzmann equation

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

$$n_\chi \sim \left. \frac{3H}{\langle \sigma v \rangle} \right|_{\text{frezeout}}$$

$$T_{\text{Freezeout}} \sim m_\chi / 30$$

$$\Omega_\chi h^2 \sim 0.1 \left(\frac{\langle \sigma v \rangle}{\left(0.1/\text{TeV} \right)^2} \right)$$



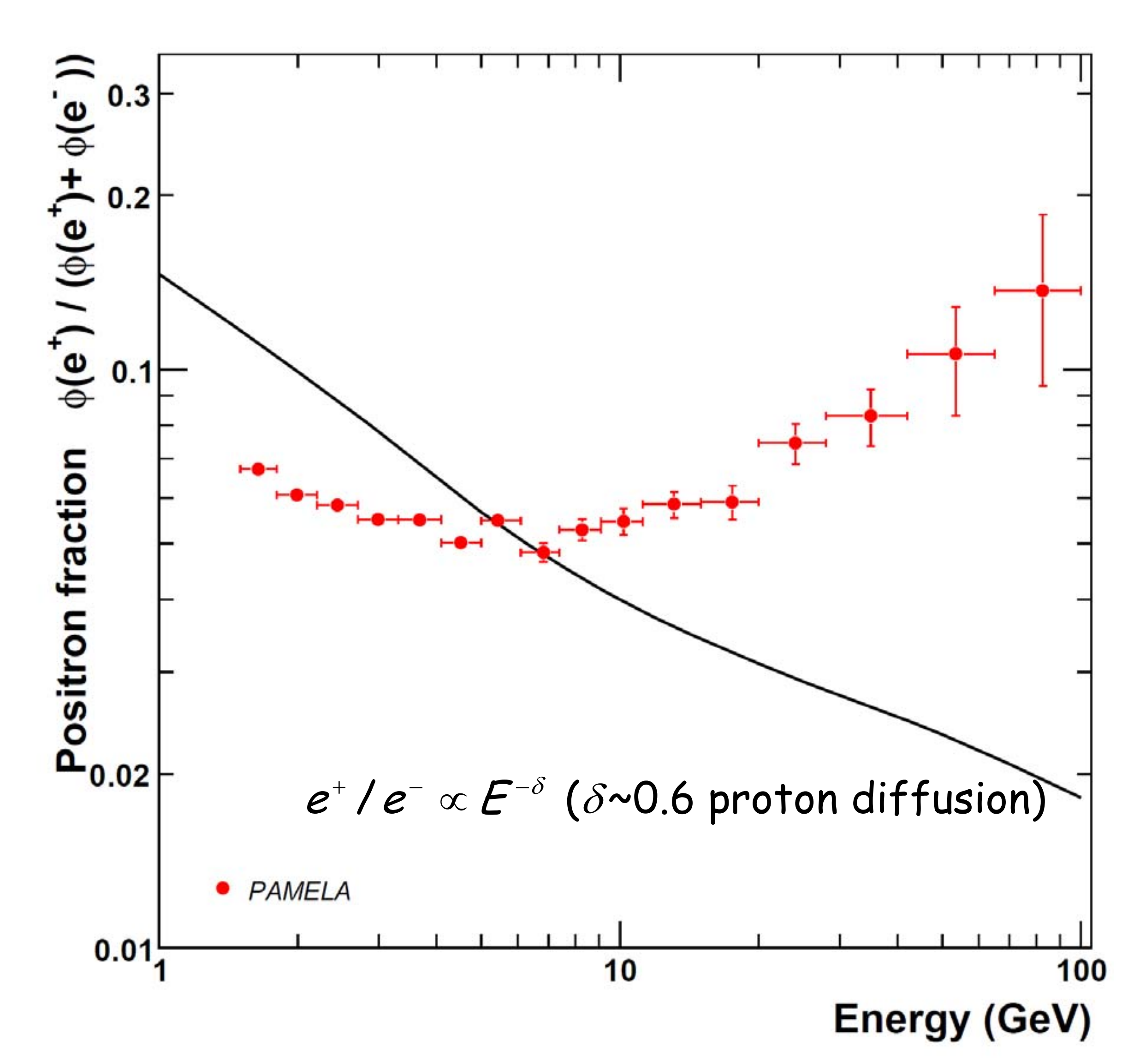
Kolb & Turner

Ω does not depend on m

Predicting TeV Physics!!!

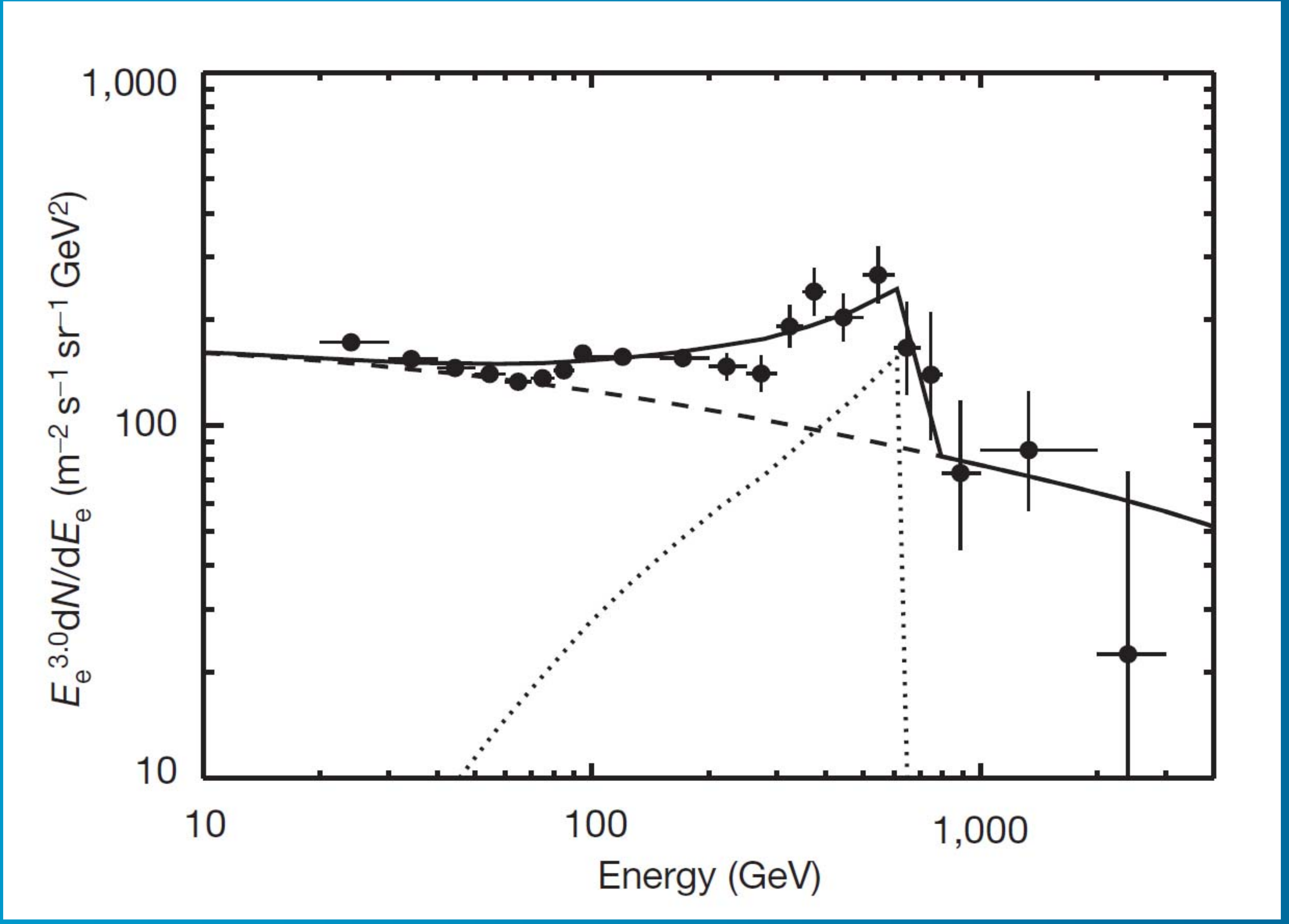
$$\langle \sigma v \rangle = 3 \times 10^{-26} cm^3 / s$$

Positron Excess (PAMELA satellite reported)



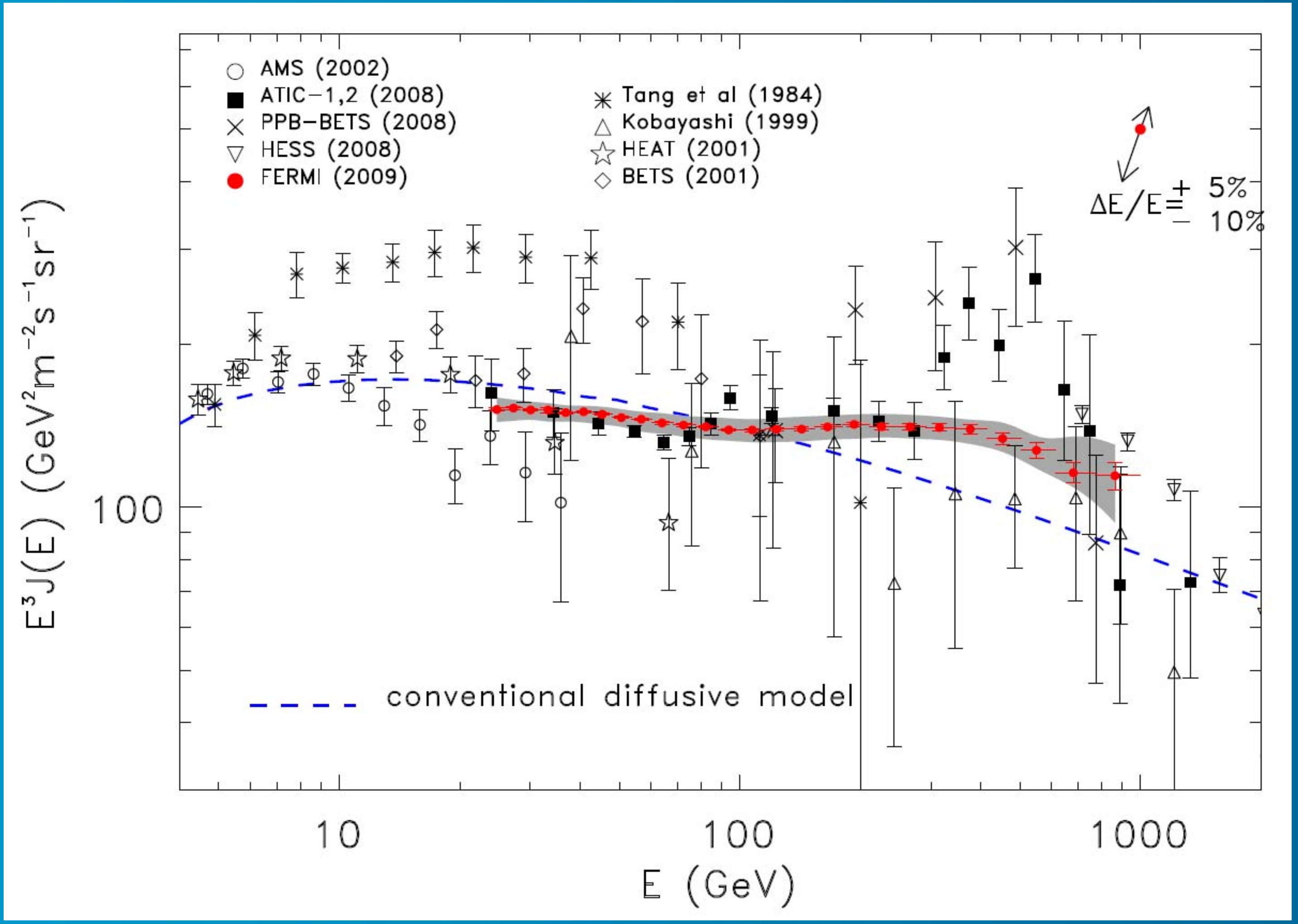
Adriani et al, arXiv:0810.4995v1 [astro-ph]

Electron and positron flux by ATIC2



Chang et al (08)

Electron and positron flux by Fermi



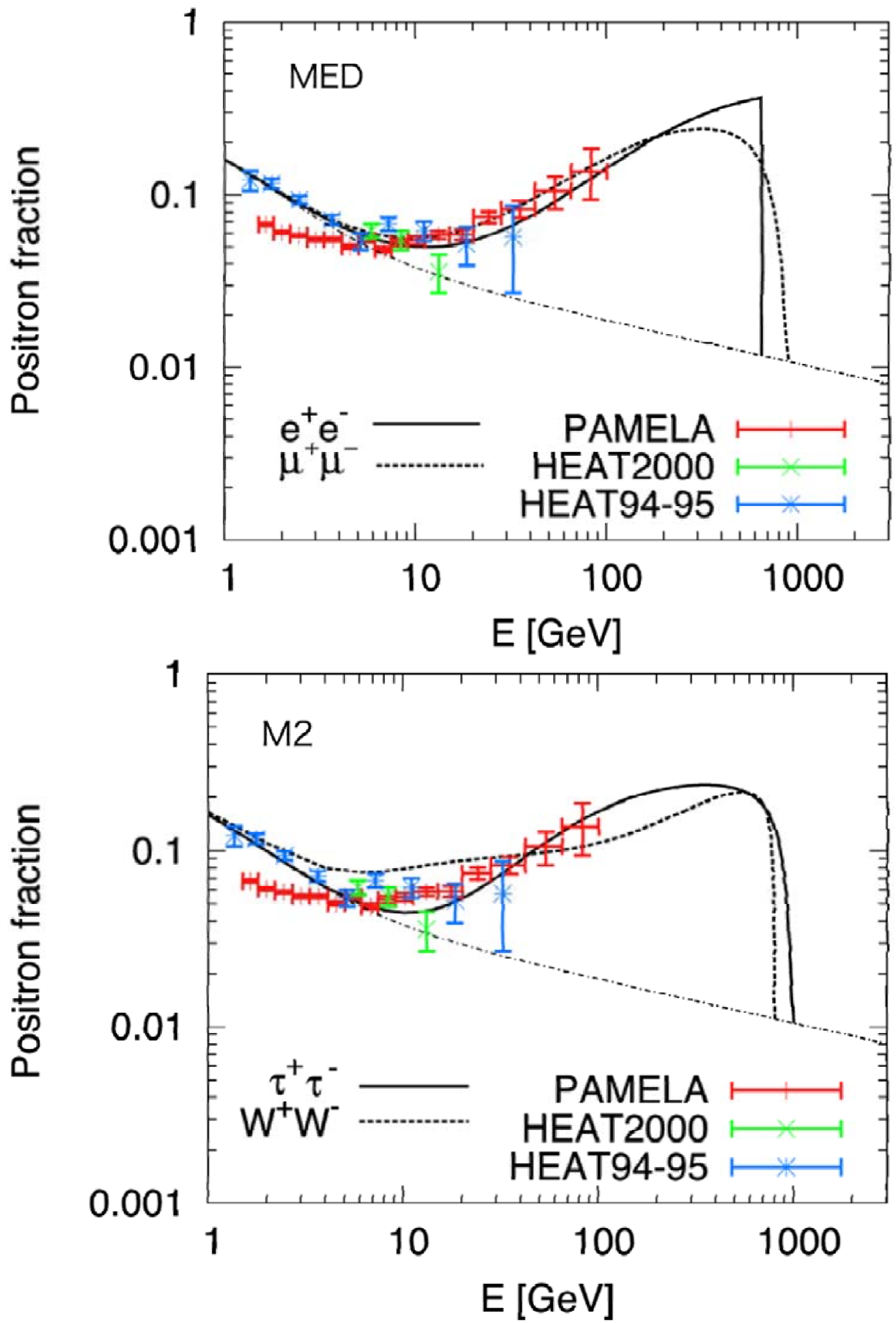
Abdo et al, Fermi LAT Collaboration, **arXiv:0905.0025, PRL102** (09) 181101

Positron excess in DM annihilation

Hisano, Kawasaki,
Kohri, Moroi, Nakayama (09)

Diffusion model
Fitted to B/C ratio

$$\langle \sigma v \rangle \sim 10^{-24} - 10^{-23} cm^3/s$$

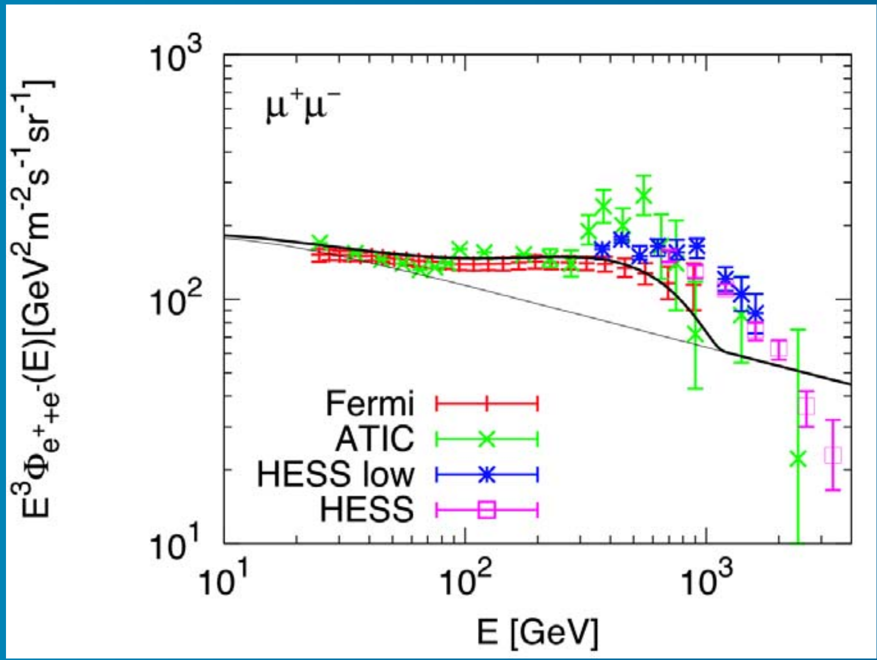


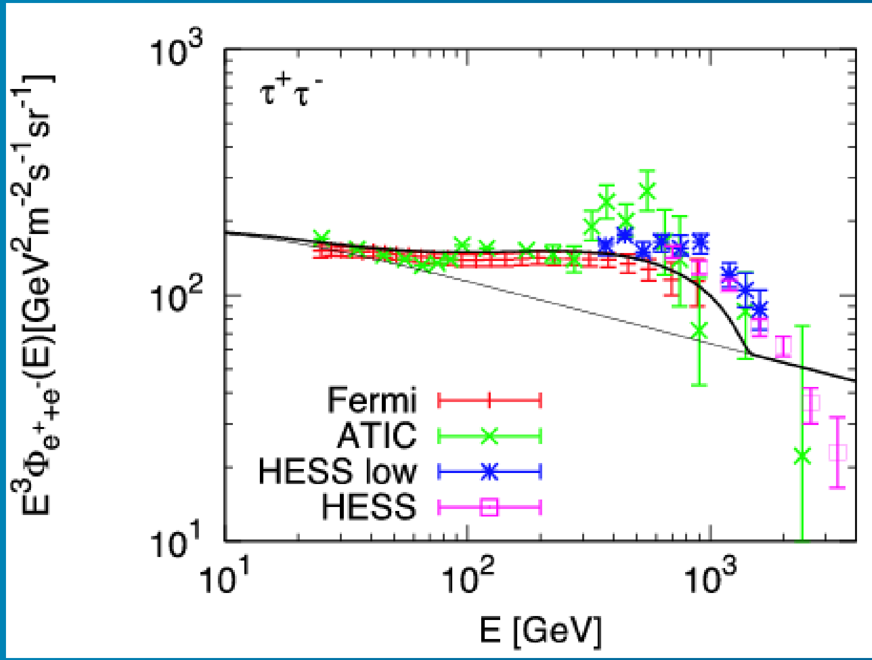
Electron/positron cutoff in DM annihilation

Hisano, Kawasaki,

Kohri, Moroi, Nakayama (09)

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



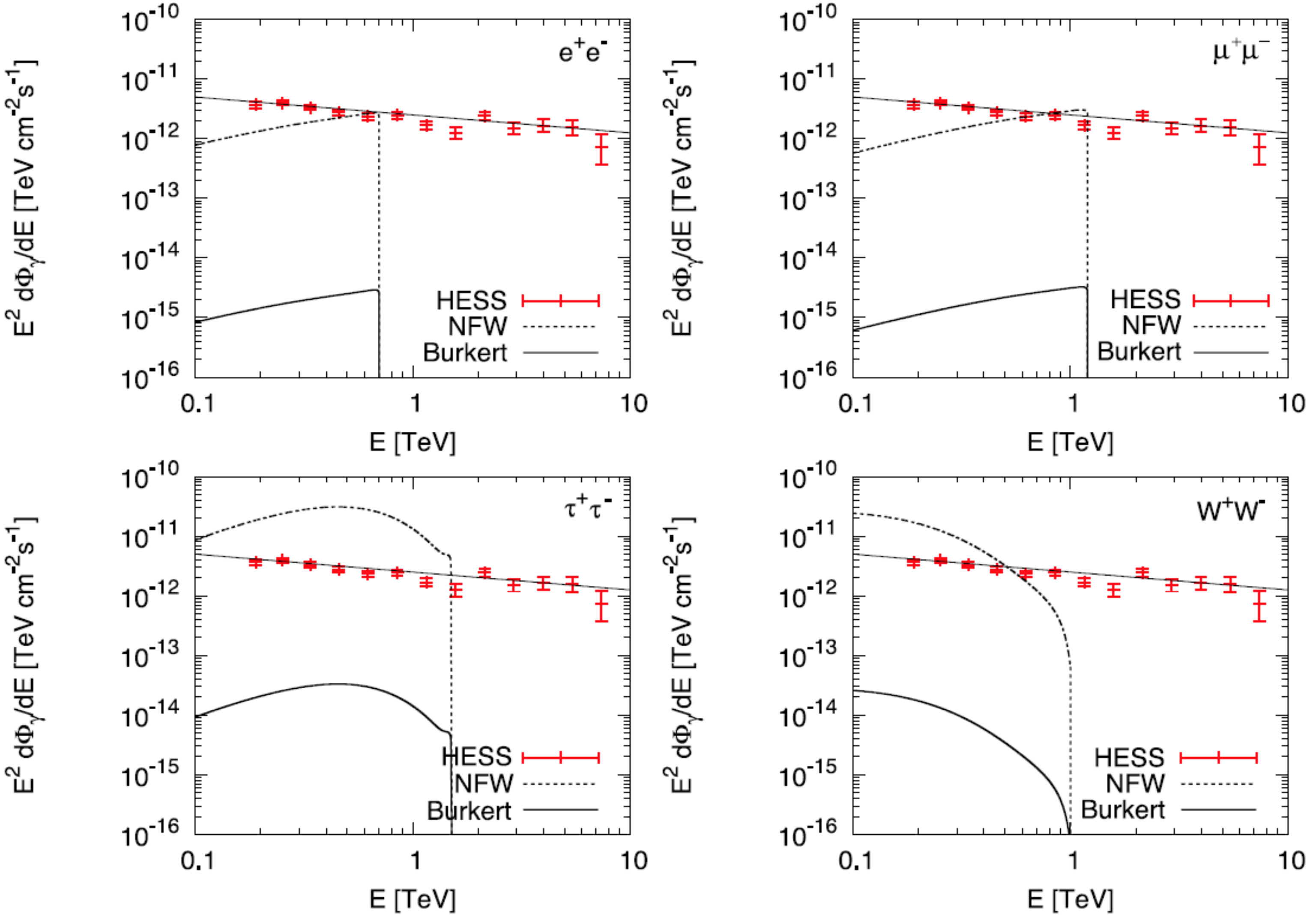


Gamma-ray signal from GC by DM annihilation

Kawasaki, Kohri, Nakayama (09)

Burkert profile [28]

$$d_{\mathrm{Bur}}(x) = \frac{1}{(1+x)(1+x^2)}.$$



Extragalactic diffuse Gamma-ray by DM annihilation

Kawasaki, Kohri, Nakayama (09)

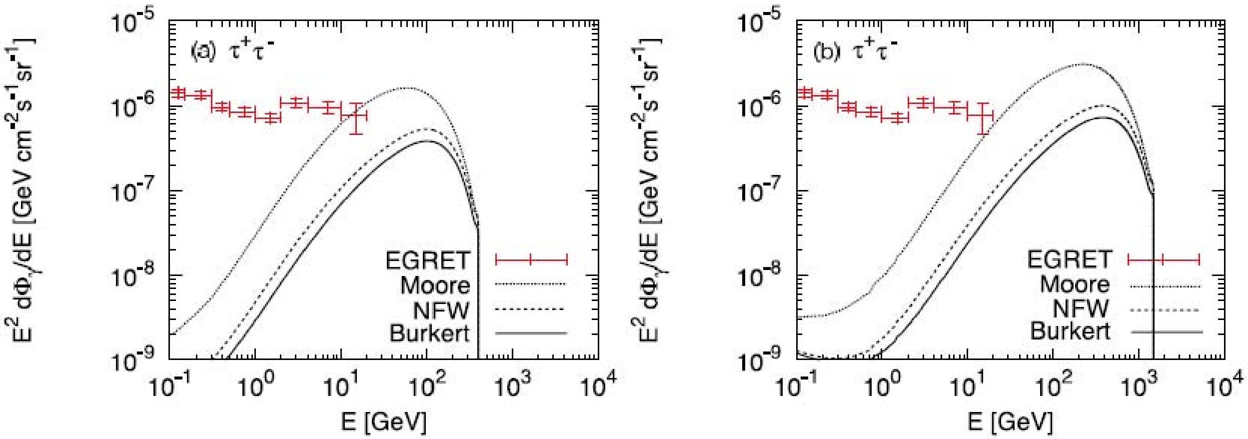


Figure 9: Same as Fig. 7, but for DM annihilating into $\tau^+\tau^-$.

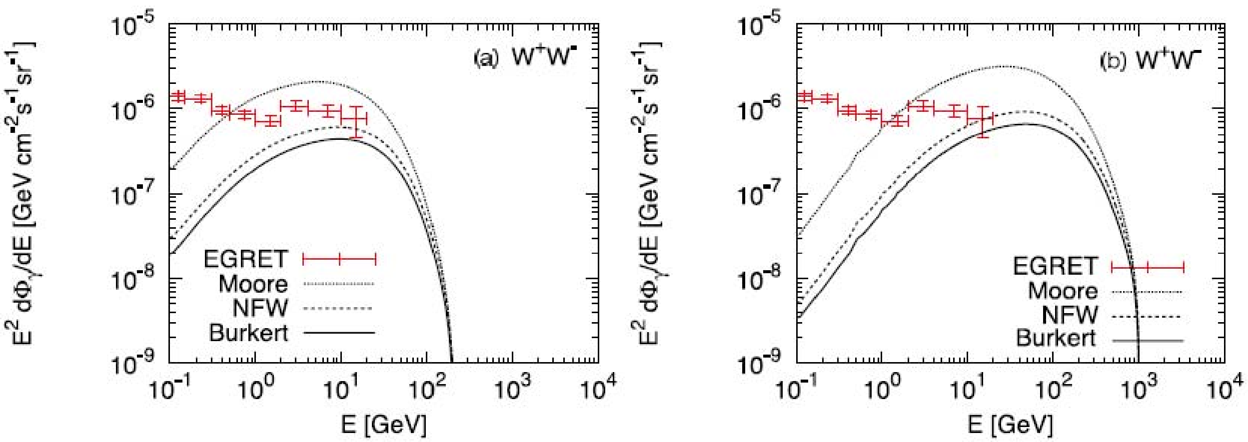
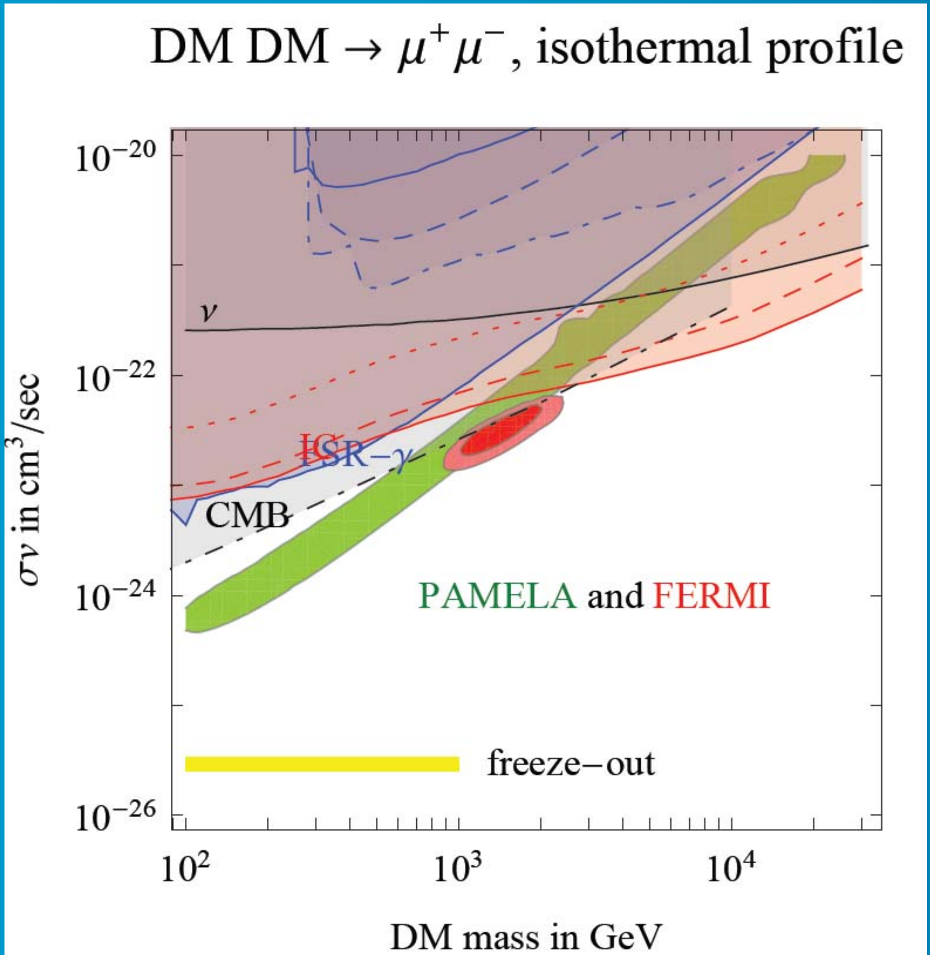


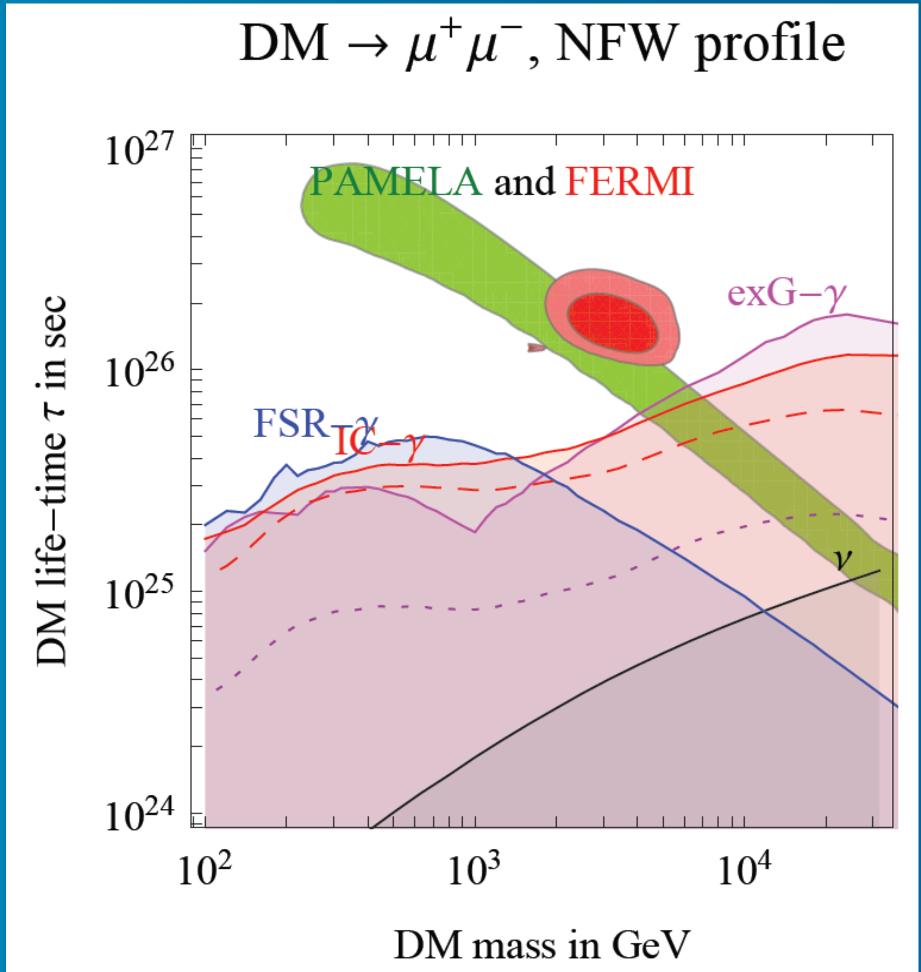
Figure 10: Same as Fig. 7, but for DM annihilating into W^+W^-.

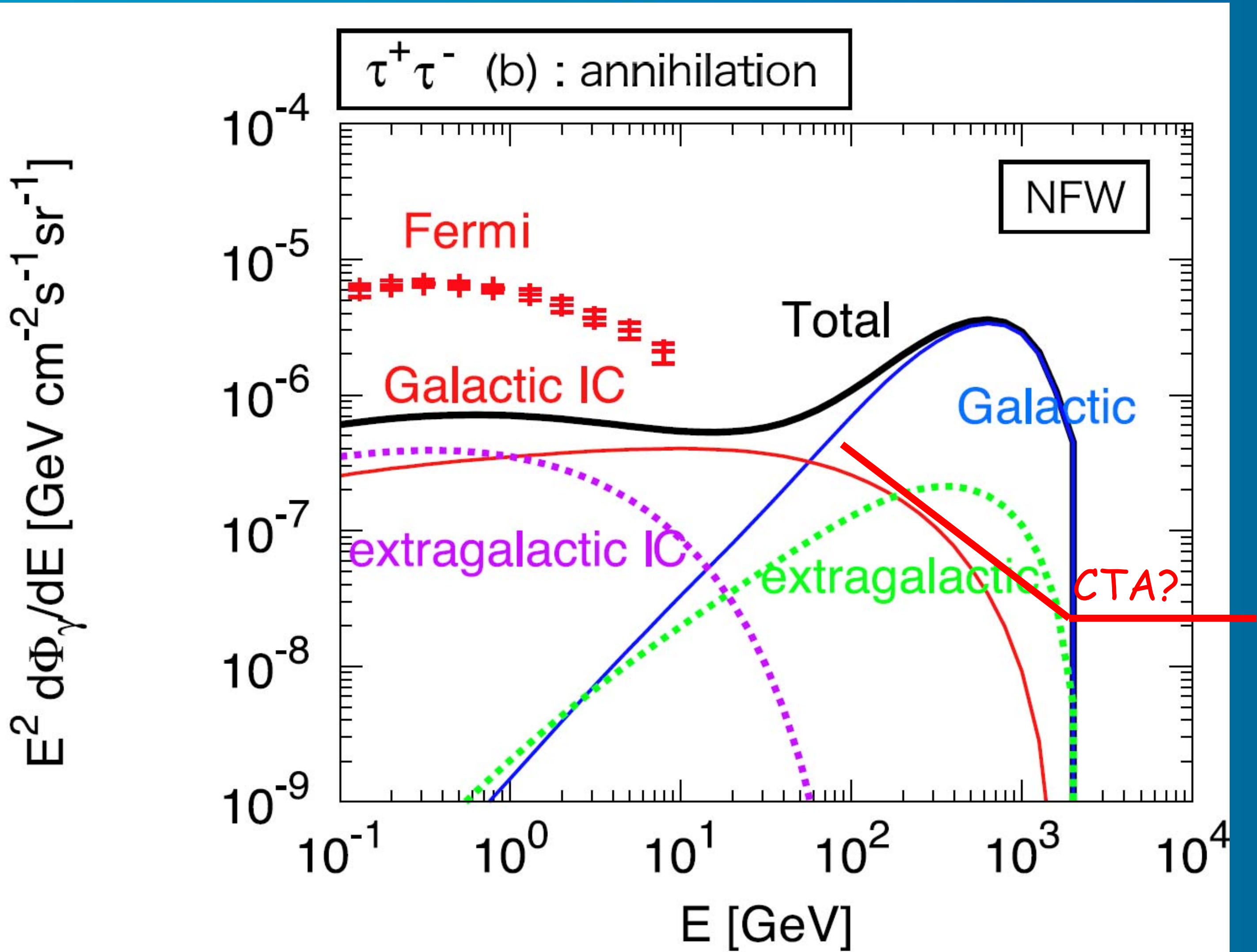
Fitting by Papucci and Strumia

Papucci, Strumia, arXiv:0912.0742 [hep-ph]

See also Chen, Mandal and F. Takahashi, arXiv:0910.2639 [hep-ph]



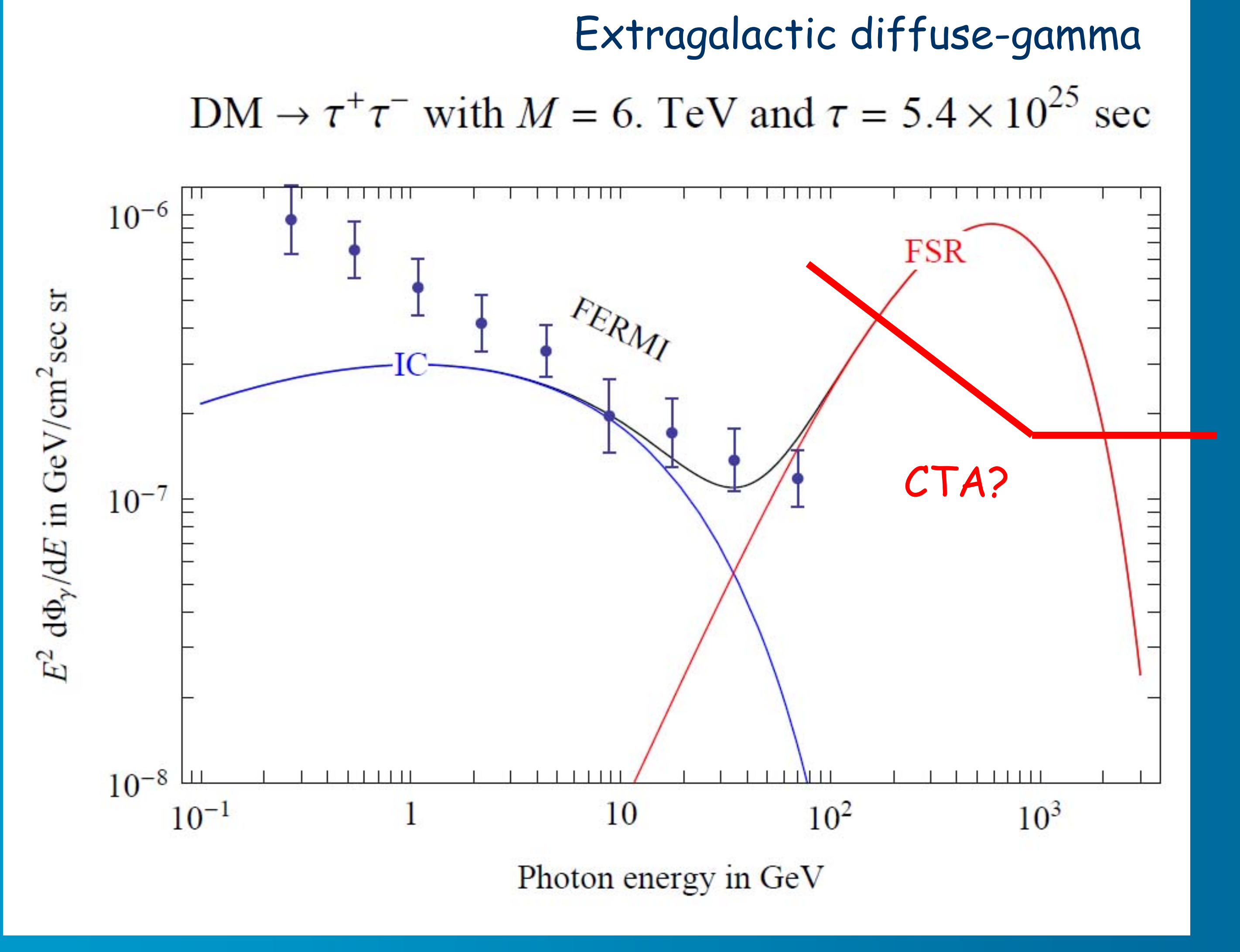




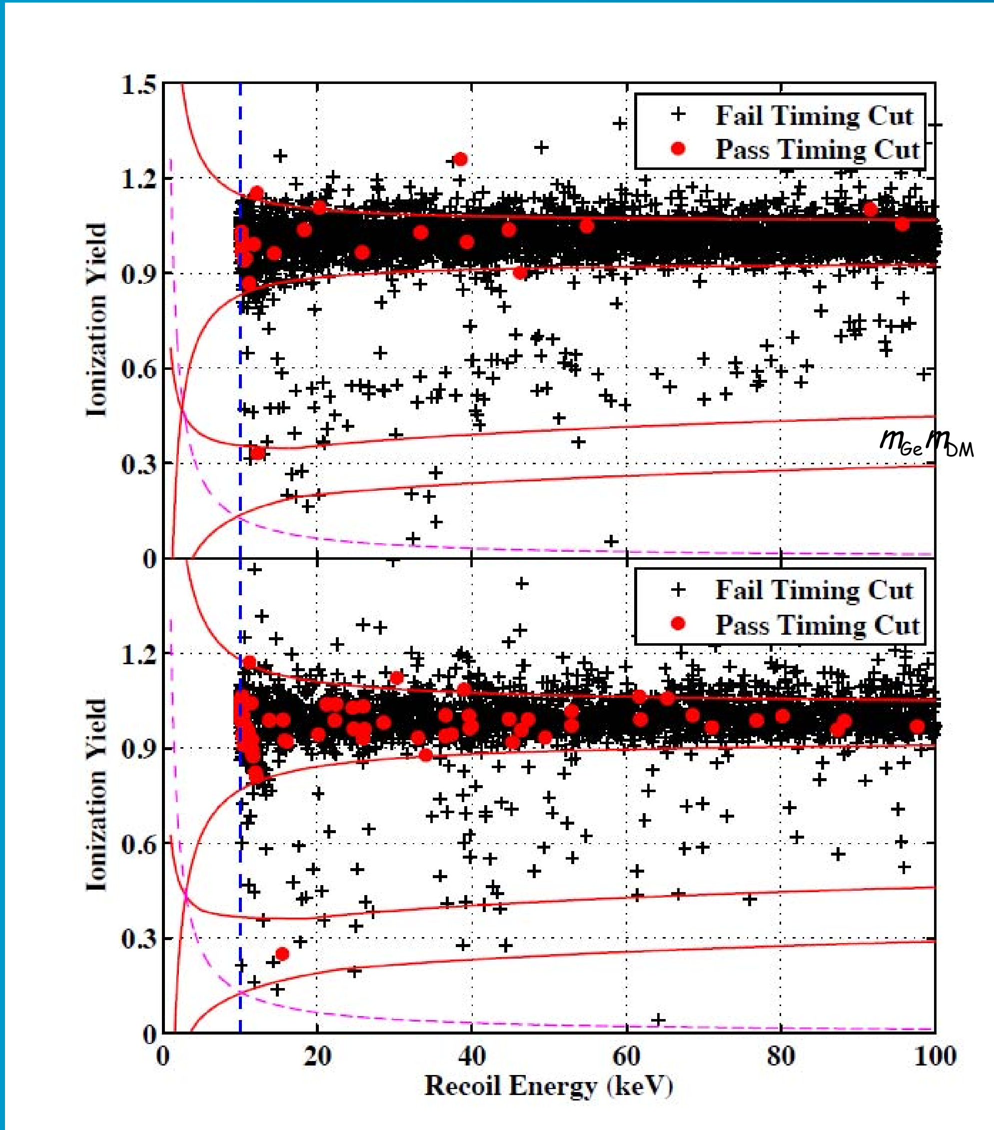
Courtesy of Kazunori Nakayama

Result of Papucci and Strumia

Papucci, Strumia, arXiv:0912.0742v1 [hep-ph]



Direct detection by CDMSII



arXiv:0912.3592v1 [astro-ph.CO]

Background

0.8 0.1(stat) 0.2(syst)

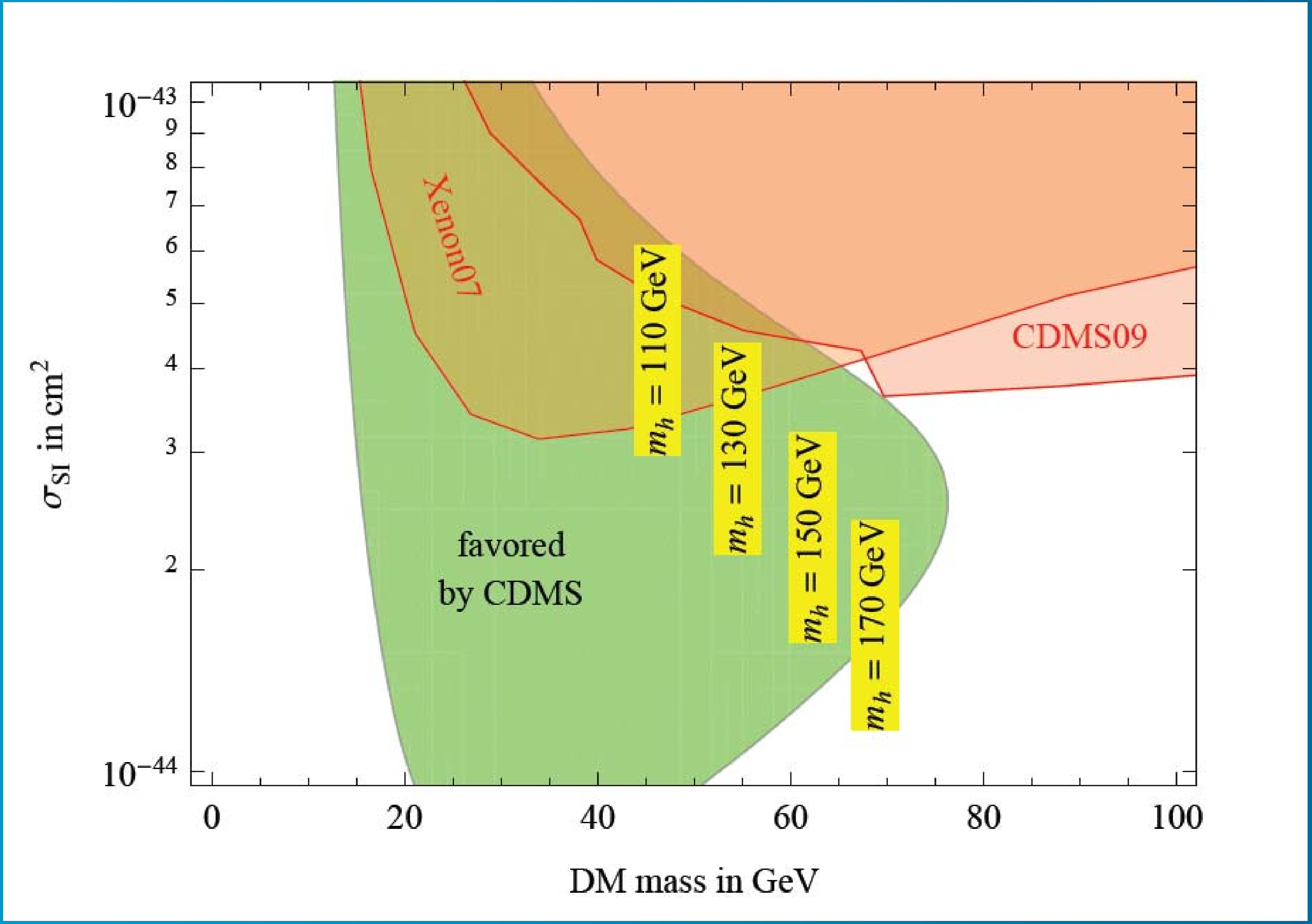
$$E_{recoil} \sim \frac{1}{2}\mu v^2 \sim O(10)\mathrm{keV}$$

$$v \sim 220\mathrm{km/s}\ (v/c{\sim}10^{-3})$$

$$\mu \sim \frac{m_{Ge}m_{DM}}{m_{Ge}+m_{DM}}$$

$$m_{Ge} = 72.6\ \mathrm{u}$$

M < O(100) GeV? (Farina et al)



Marco Farina, Duccio Pappadopulo, Alessandro Strumia   arXiv:0912.5038v1 [hep-ph]

Conclusion

- Fermi may not exclude the possible scenarios for the positron/electron excess by the DM annihilation/decay because of the upper limit on the sensitivity (<300 GeV)

- CTA will be able to verify those scenarios

- CTA may have a sufficient sensitivity to detect gamma-rays associated with DM annihilation even with its canonical annihilation cross section ($\sim 3 \quad 10^{-26}$ cm^3/s)