# Indirect detection of dark matter

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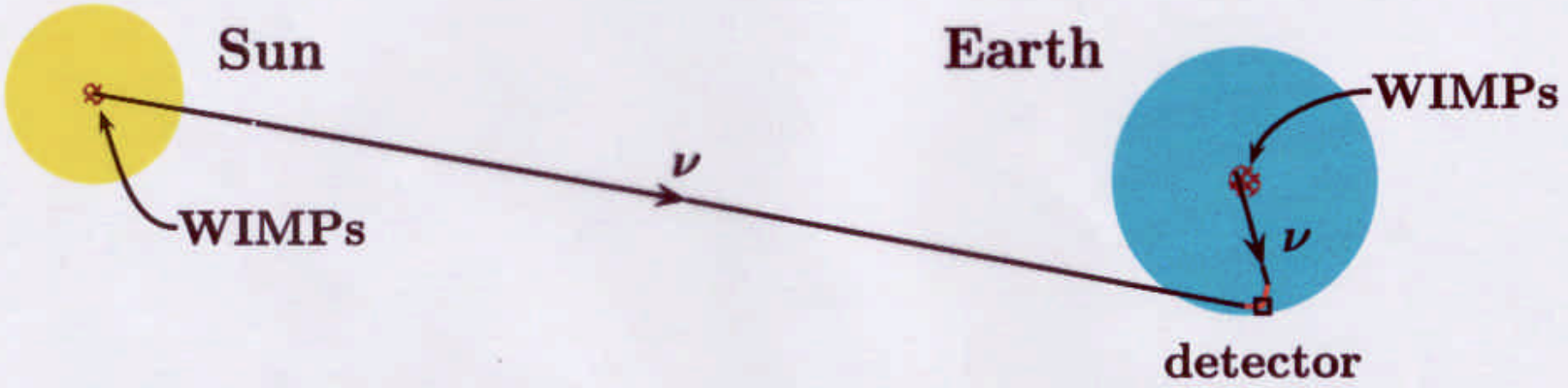
**Indirect** ***adj*** (a) not direct; (b) not going straight to the point; (c) not straightforward and open, deceitful.

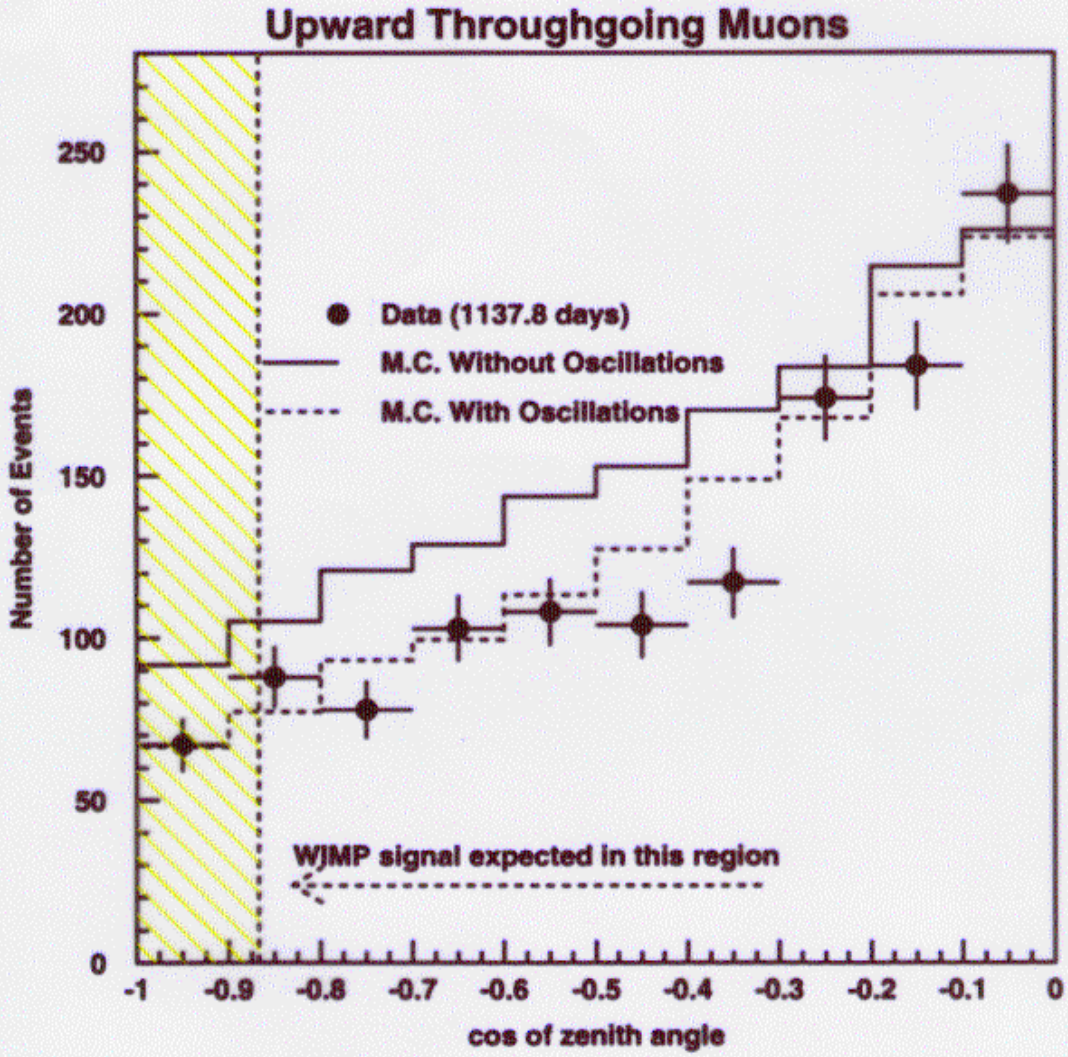
# Searching for dark WIMPs

- direct detection
- neutrinos from Sun/Earth
- anomalous cosmic rays from galactic halo
- neutrinos, gamma-rays, radio waves from galactic center

# Neutrinos from Sun/Earth

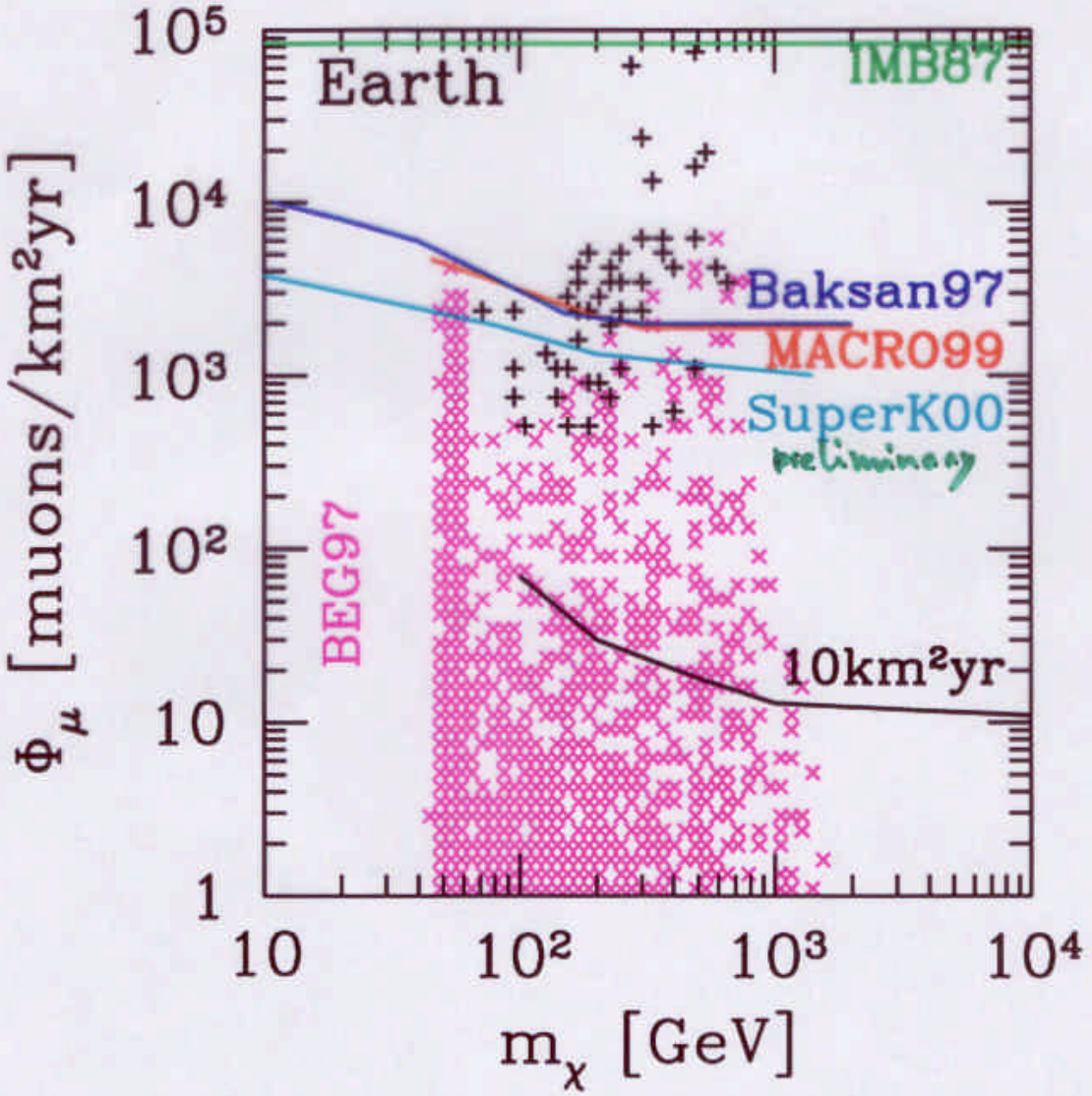
**Earth: Freese 1986, Krauss,Srednicki,Wilczek 1986**
**Sun: Silk,Olive,Srednicki 1986**



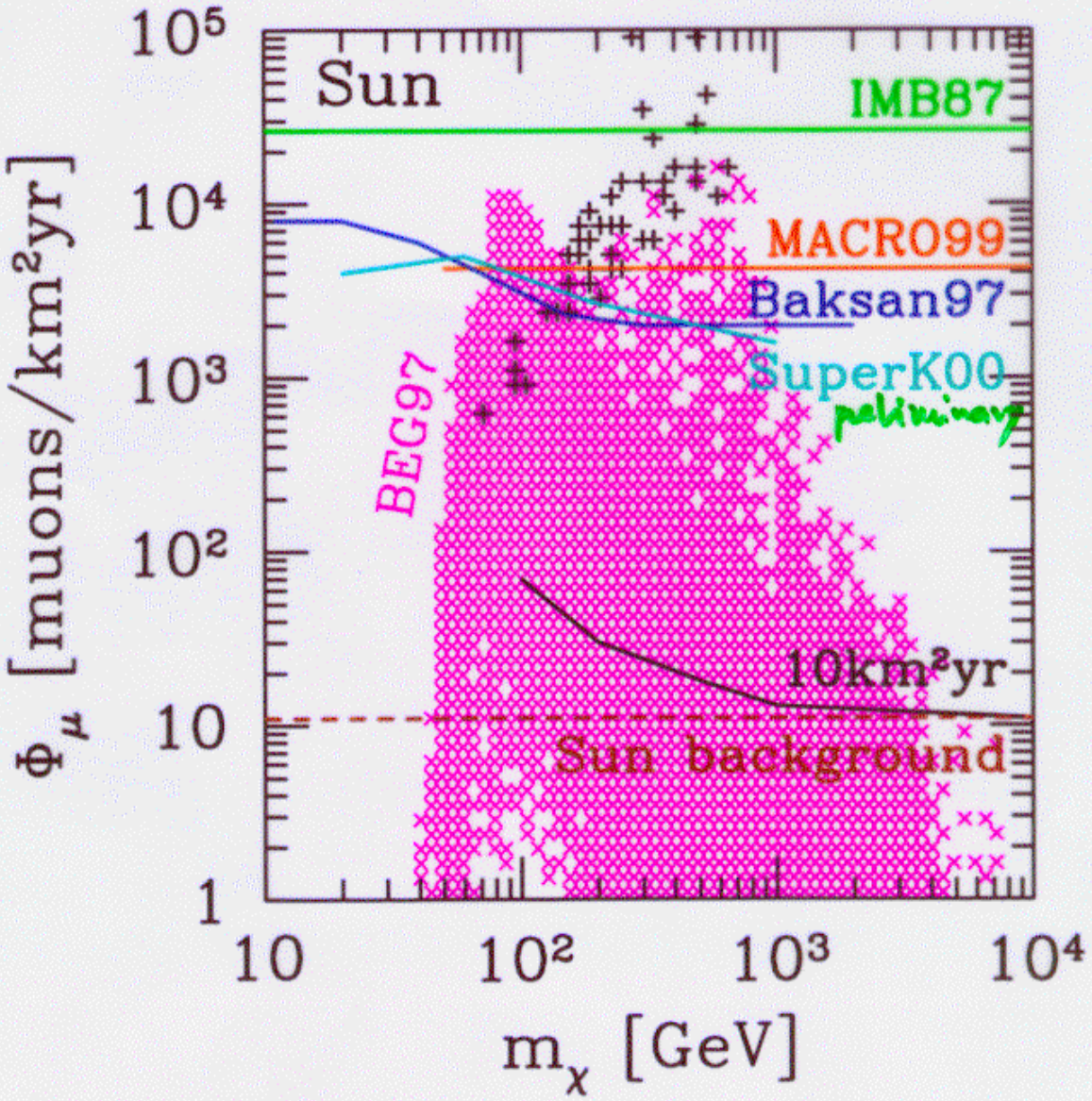



*Super-K 2000*
PRELIMINARY

# WIMP neutrinos from Earth



# WIMP neutrinos from Sun



# Anomalous cosmic rays from annihilation in galactic halo

Gunn et al 1978, Stecker 1978

$$\chi\chi \longrightarrow f\bar{f}, HH, WW, ZZ, gg, \gamma\gamma \longrightarrow \ldots$$

$$\ldots \longrightarrow e^+, \bar{p}, \gamma, \nu$$

## Annihilation rate per unit volume

annihilation cross section — relative velocity

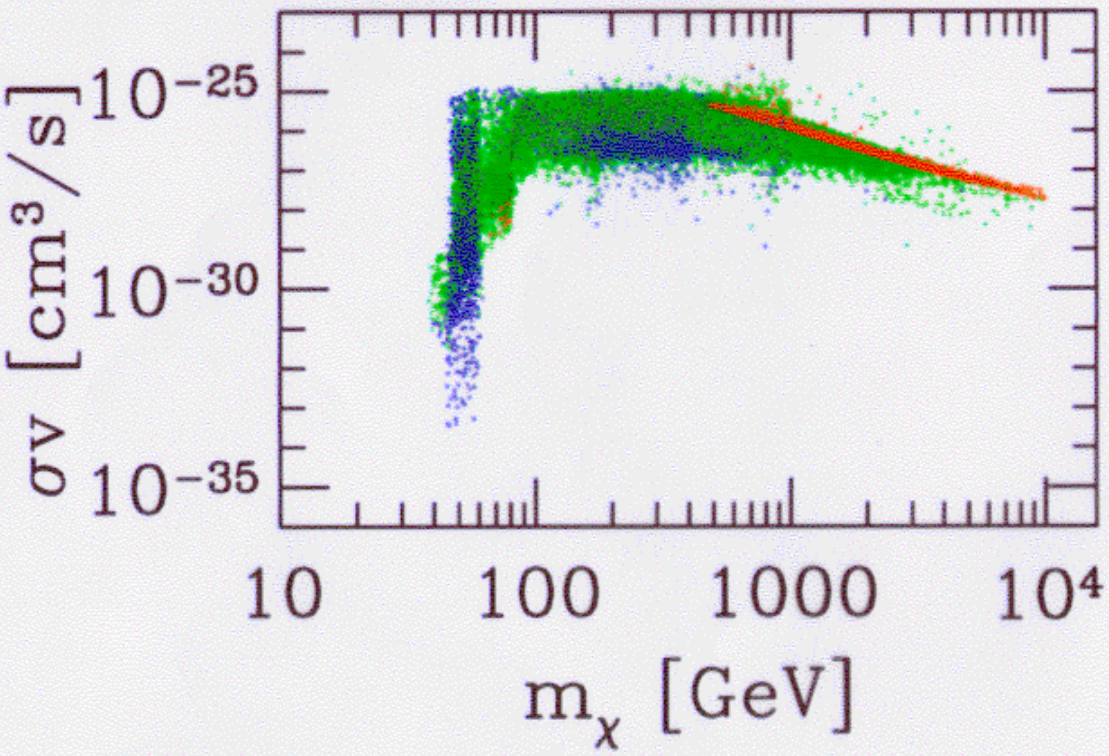
$$\Gamma_{\rm ann} = \frac{\sigma v}{m^2} \rho^2$$

mass — dark matter density

# Annihilation cross section

- $\sigma v \to$ const for $v \to 0$
- in general, not function of mass only

example: neutralino



# Density profile of dark halo

**with cores (empirical)**

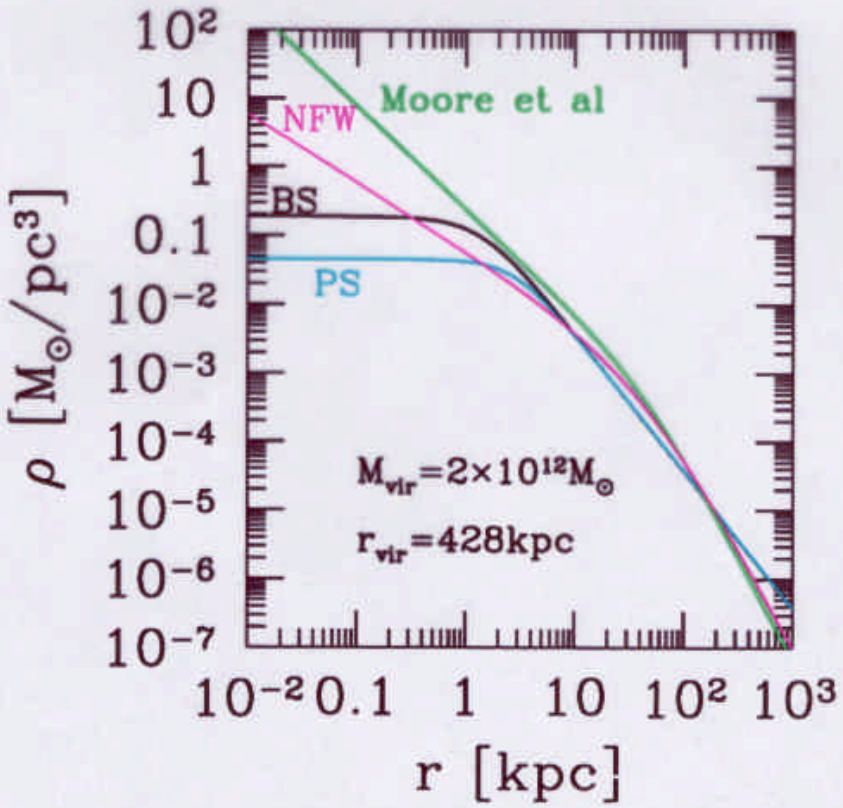
$\rho \sim$ const at $r \to 0$

e.g. Bahcall, Soneira 1980; Persic, Salucci 1996

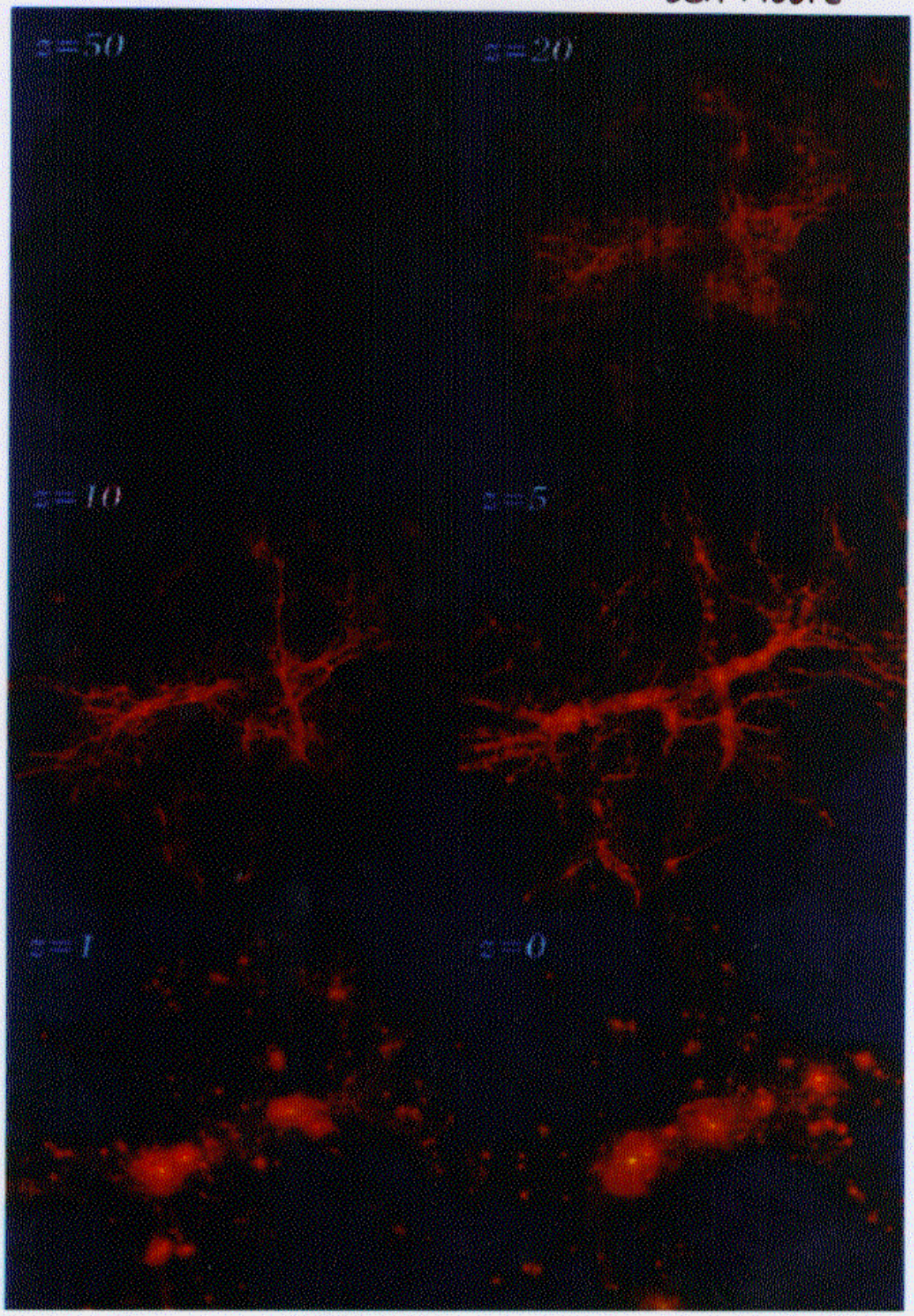
**with cusps (from theory of galaxy formation)**

$\rho \sim r^{-\gamma}$ at $r \to 0$

e.g. Navarro, Frenk, White 1996; Moore et al. 1999



Ben Moore



# Cold dark matter models predict cuspy dark halos

$$\rho \propto r^{-\gamma}$$

## Semi-analytical

**(self-similar evolution)**

$2 \leq \gamma < 2.25$ Hoffman, Shaham 1985

$\gamma \simeq 1$ Subramanian 1999

## N-body simulations

**(do not extend to center)**

$\gamma = 0.3$ Kravtsov et al 1998

$\gamma = 1.0$ Navarro, Frenk, White 1996

$\gamma = 1.5$ Fukushige, Makino 1997; Moore et al 1998; Ghigna et al 1999

- origin of cusps is not well understood
- existence of cusps in real galaxies and galaxy clusters is unclear

**The community is divided!**

# Gamma-rays from galactic halo

Gunn et al & Stecker 1978

## Continuum from hadrons

Silk,Srednicki 1984

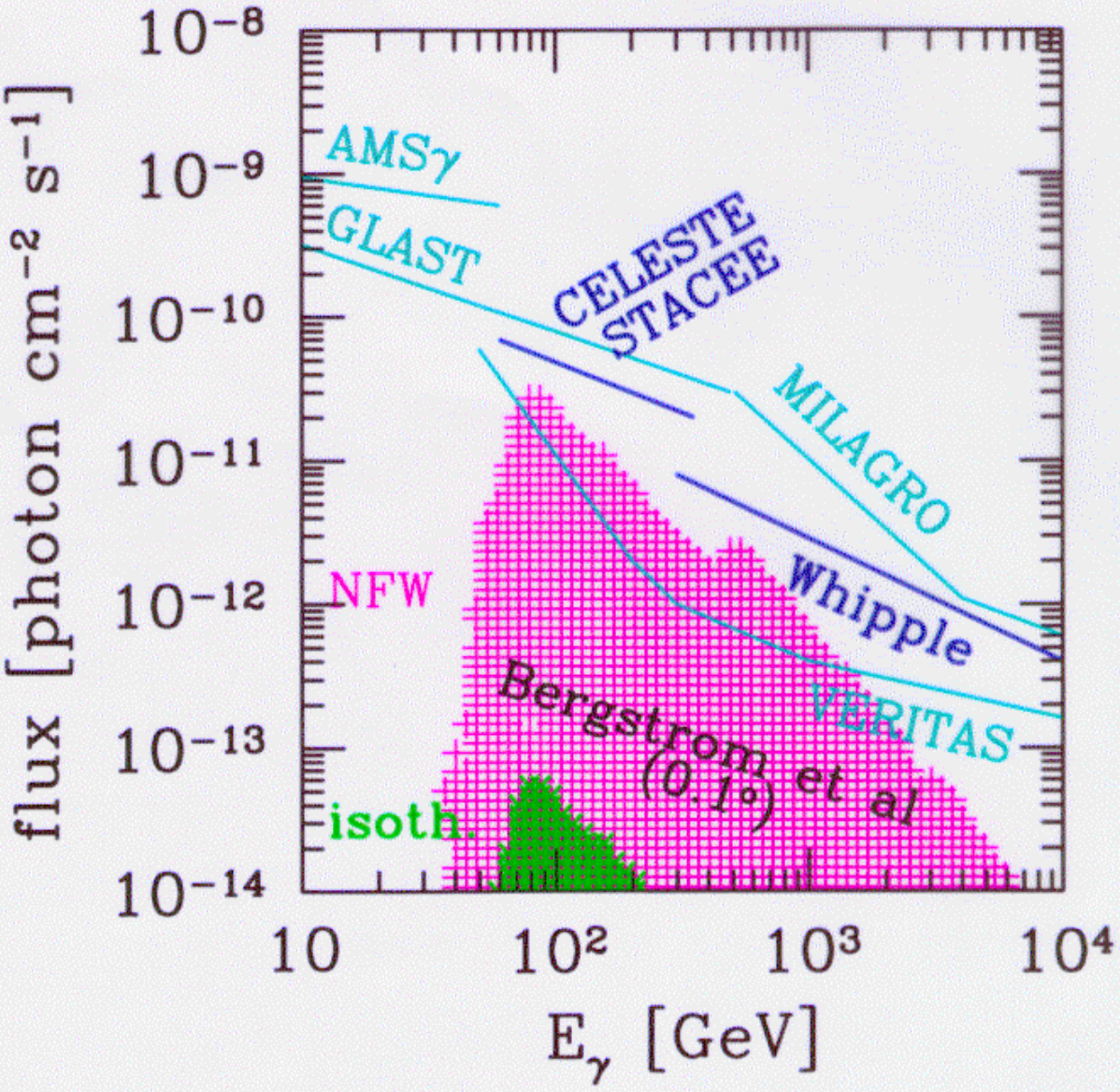
- sky distribution similar to inverse Compton emission
- spectral shape may help

## Line from $\gamma\gamma$, $Z\gamma$

Srednicki,Theissen,Silk 1986

- no known astrophysical background
  *excellent signature!!*
- need good energy and angular resolution
- need cuspy halos

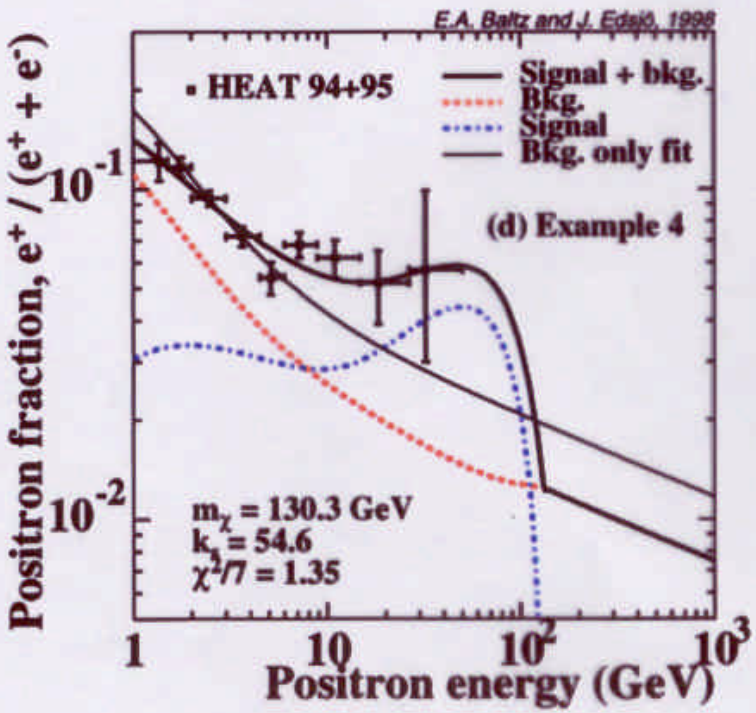
# Gamma-ray line from neutralino annihilation

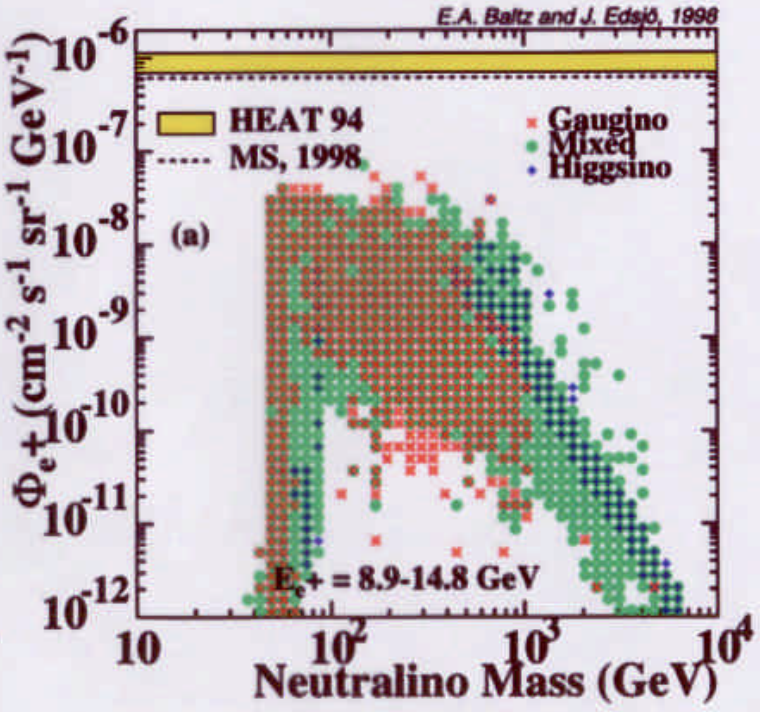


# Cosmic-ray positrons

Silk,Srednicki 1984

Excess in data has right shape for dark matter
but fluxes in MSSM are too small (Baltz,Edsjö 1999)



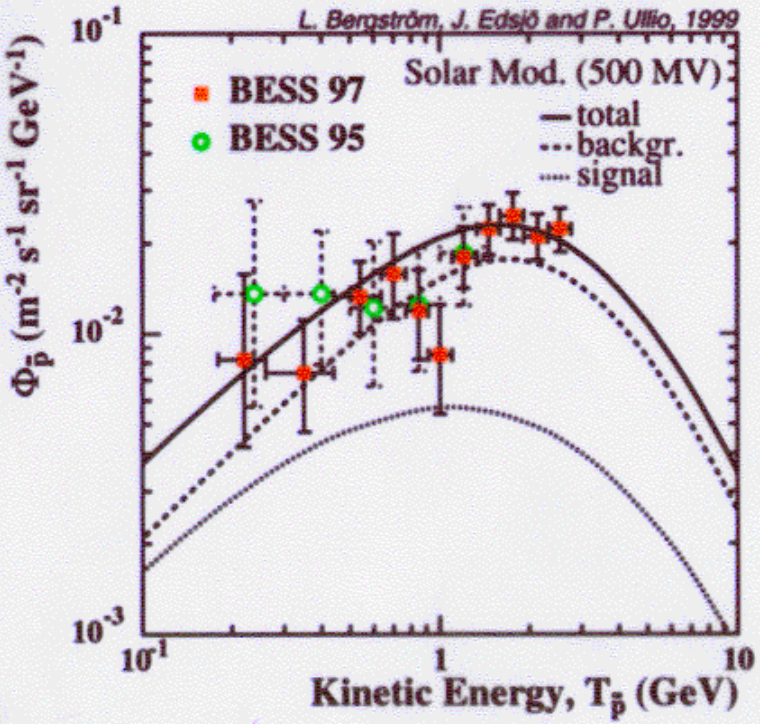



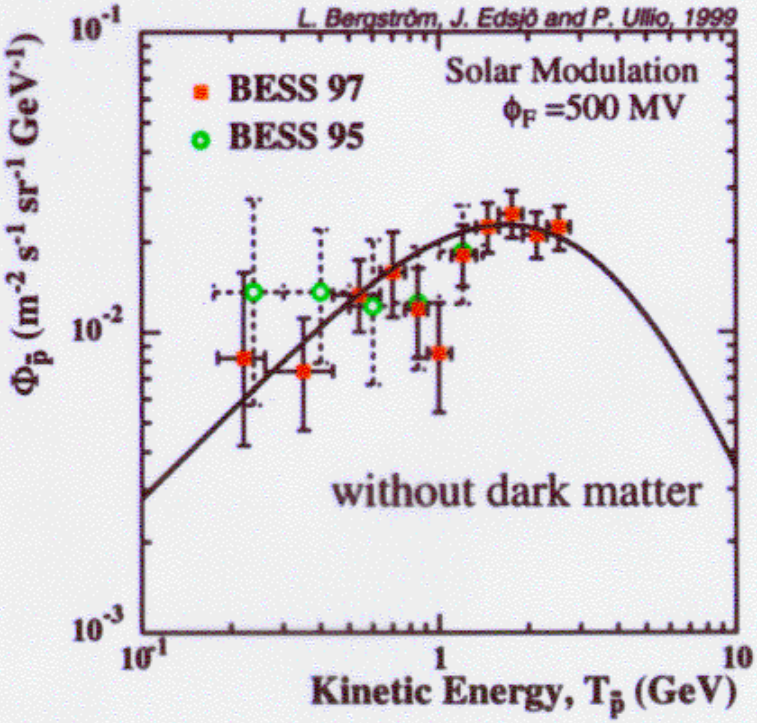
# Cosmic-ray antiprotons

**Silk,Srednicki 1984**

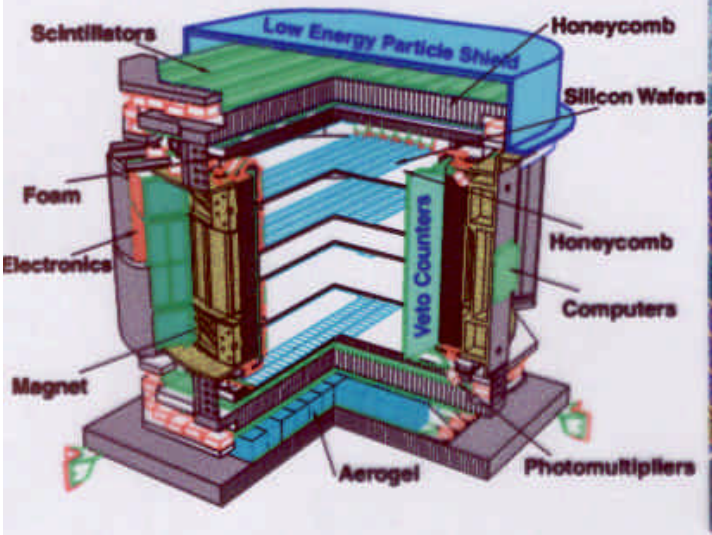
**Data can be explained both with and without dark matter (Bergström, Edsjö, Ullio 1999)**

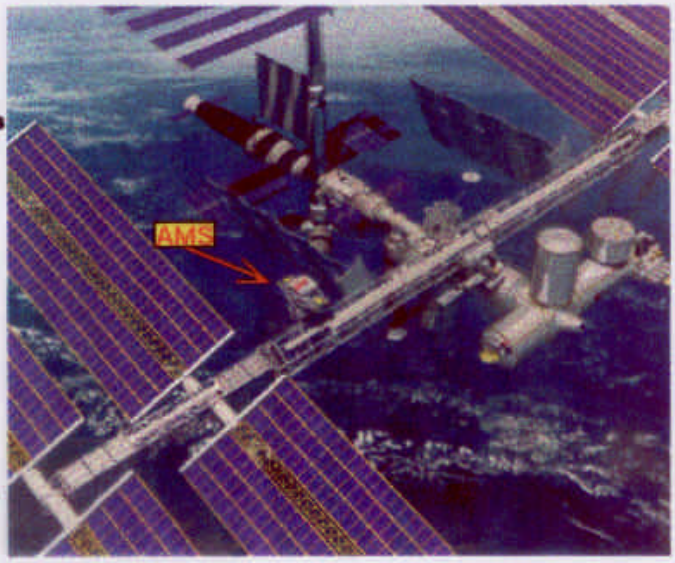
**$\bar{p}$ production off He in interstellar medium**



# AMS




**In 3 years on the International Space Station**

$\approx 10^7$ **electron events,** $E > 10\text{GeV}$

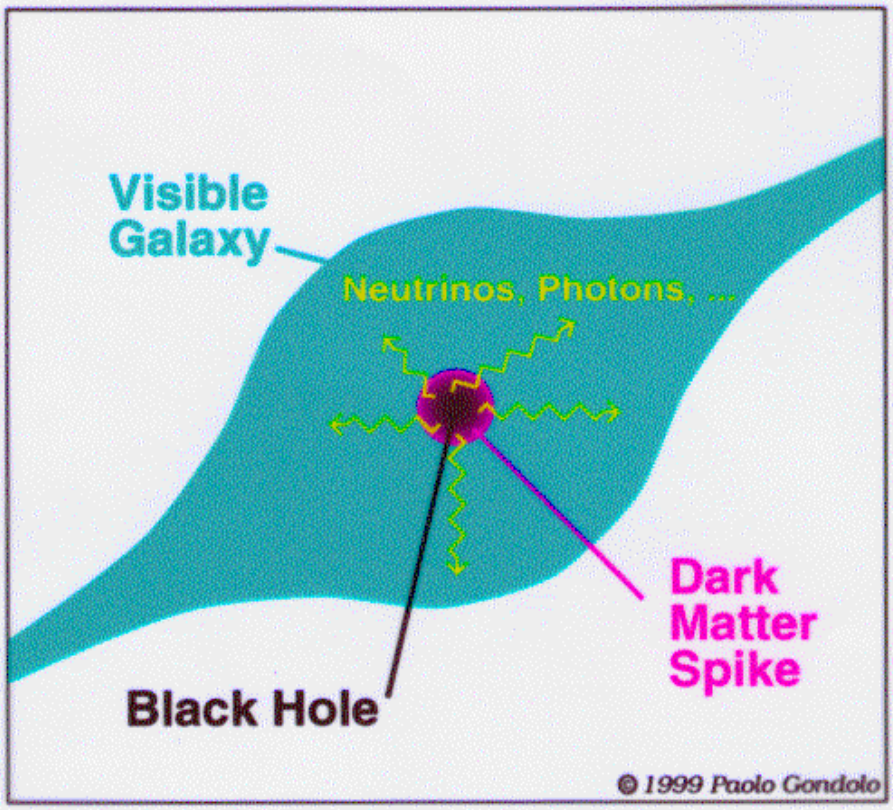
$\approx 4 \times 10^6$ **positron events,** $E > 5\text{GeV}$

$\approx 10^6$ **proton events,** $E > 1\text{TeV}$

$\approx 10^6$ **antiproton events,** $E > 5\text{GeV}$

# Neutralinos at the galactic center

**Gondolo Silk 1999, Gondolo 2000**

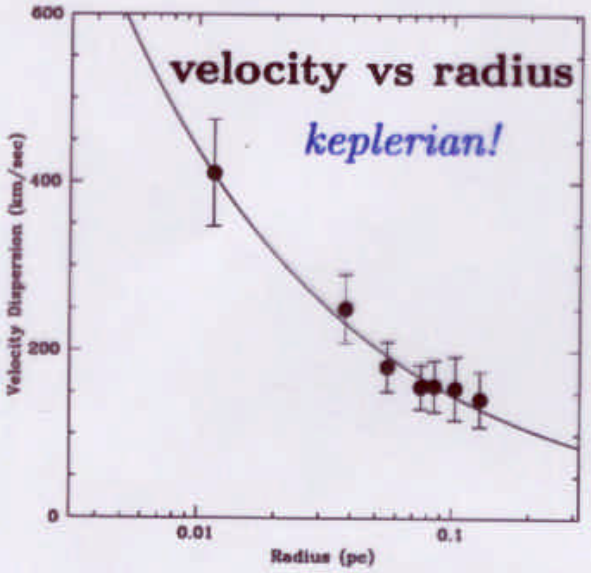


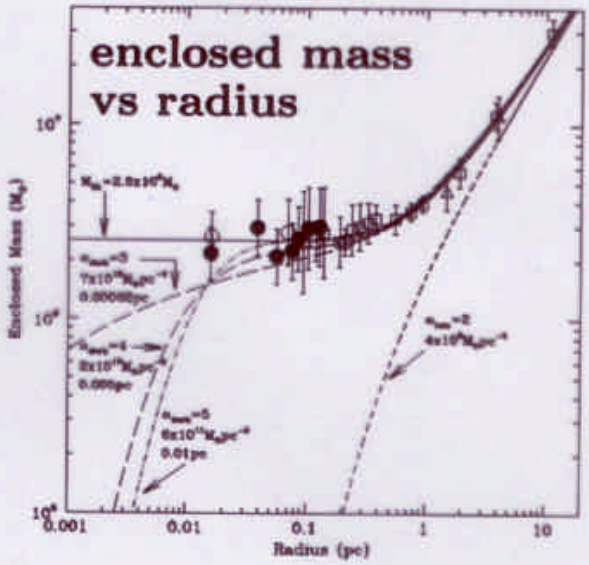

- new source of neutrinos and $\gamma$-rays
- either neutralino dark matter or cuspy dark halos

# Black hole at galactic center

## Kinematics of stars in central region

**(Eckart, Genzel 1996, 2000; Ghez et al. 1998)**



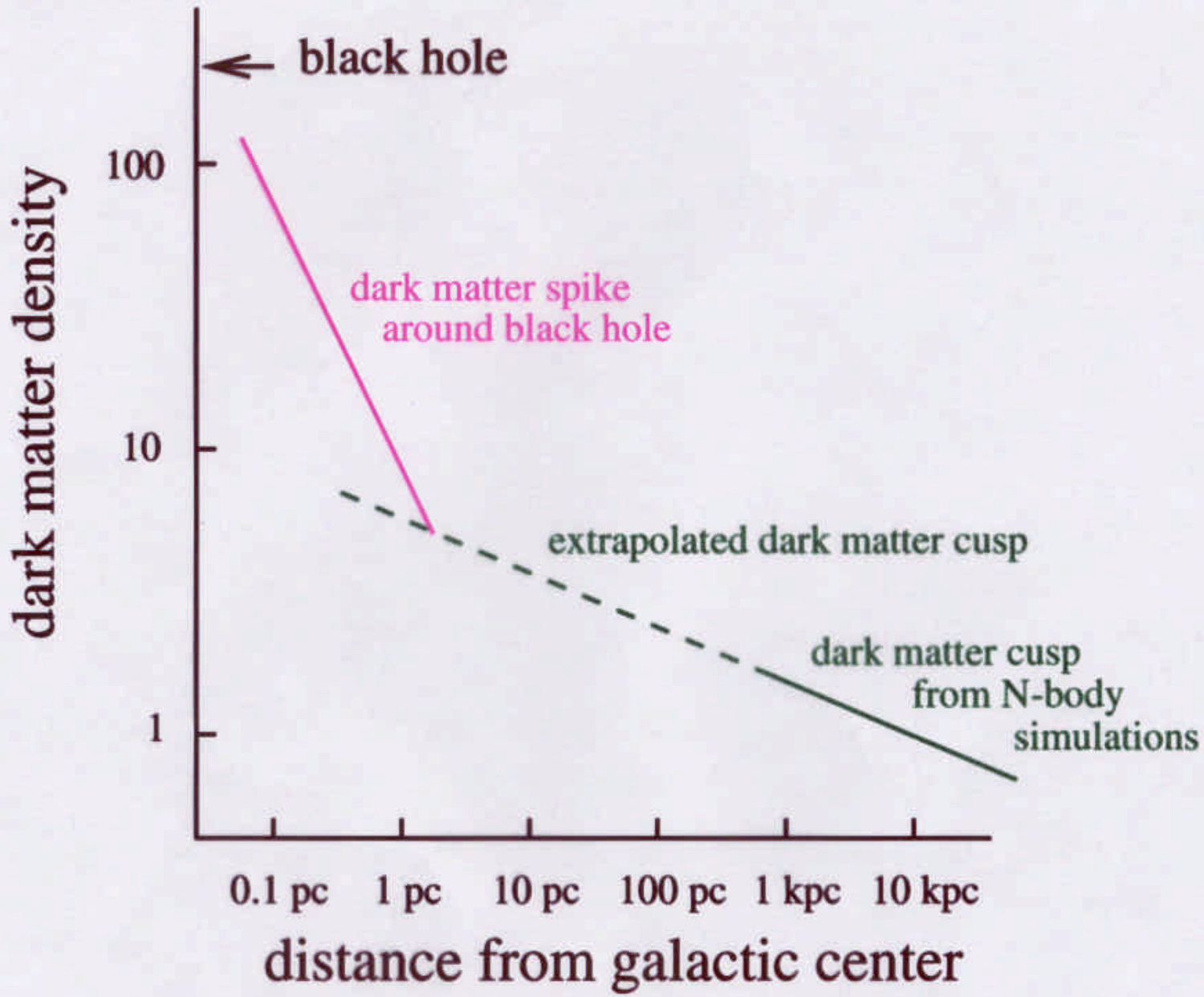




**Black hole mass $(2.6 \pm 0.2) \times 10^6 M_\odot$**

If dark matter fell

into a black hole,

would anybody notice?


black hole
dark matter density
100
10
1
dark matter spike
around black hole
extrapolated dark matter cusp
dark matter cusp
from N-body
simulations
0.1 pc
1 pc
10 pc
100 pc
1 kpc
10 kpc
distance from galactic center

# Dark matter signals from galactic center

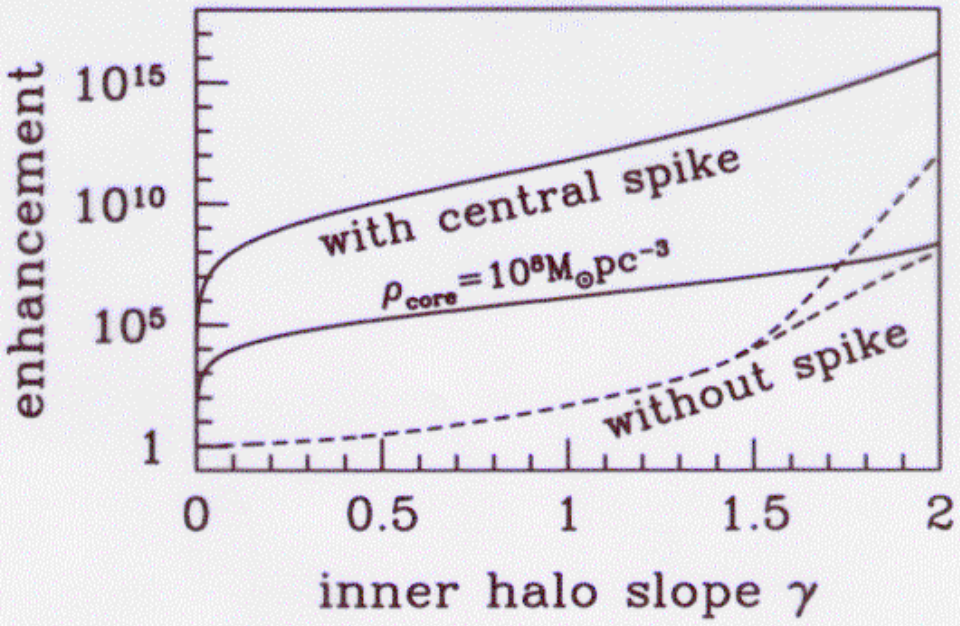
Gondolo, Silk 1999

**Photons, positrons, antiprotons, neutrinos**

$$\text{flux} = \text{flux(halo)} + \text{flux(spike)}$$

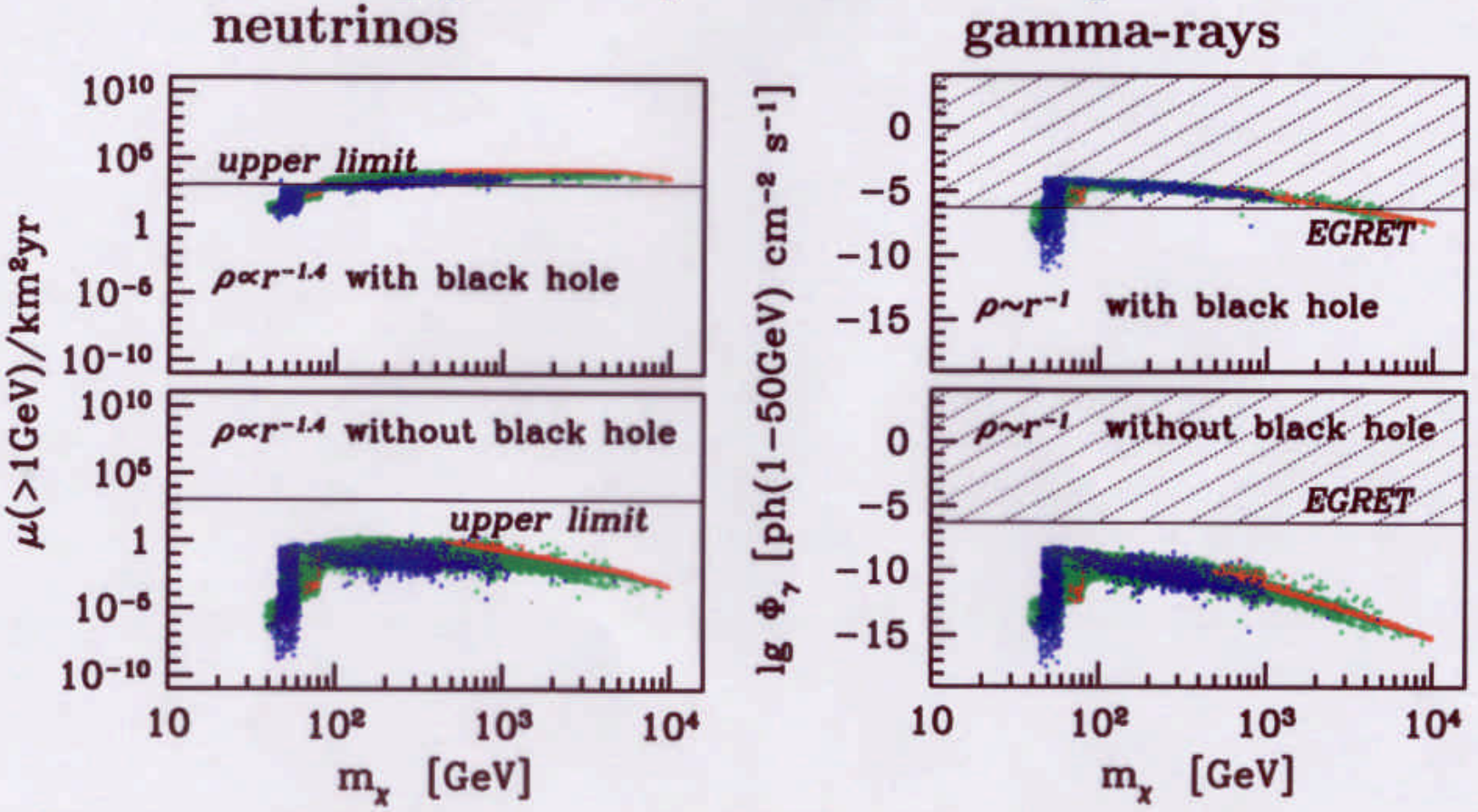
**Halos with cusps: big enhancement.**

**Halos with cores: no enhancement.**



# Limits on neutralino dark matter in cuspy halos

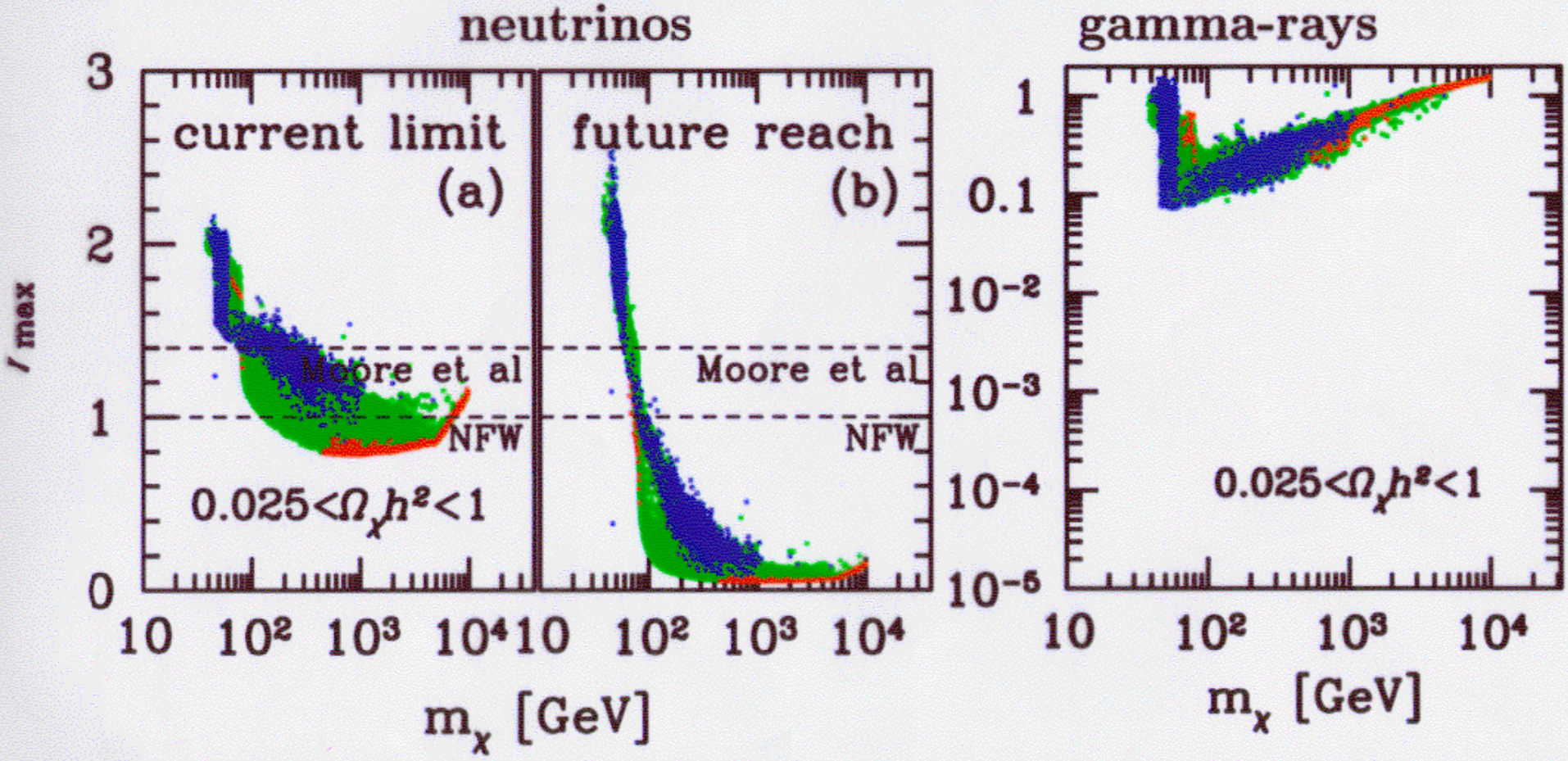
## *Cuspy halo plus central spike*



# Information on inner dark halo

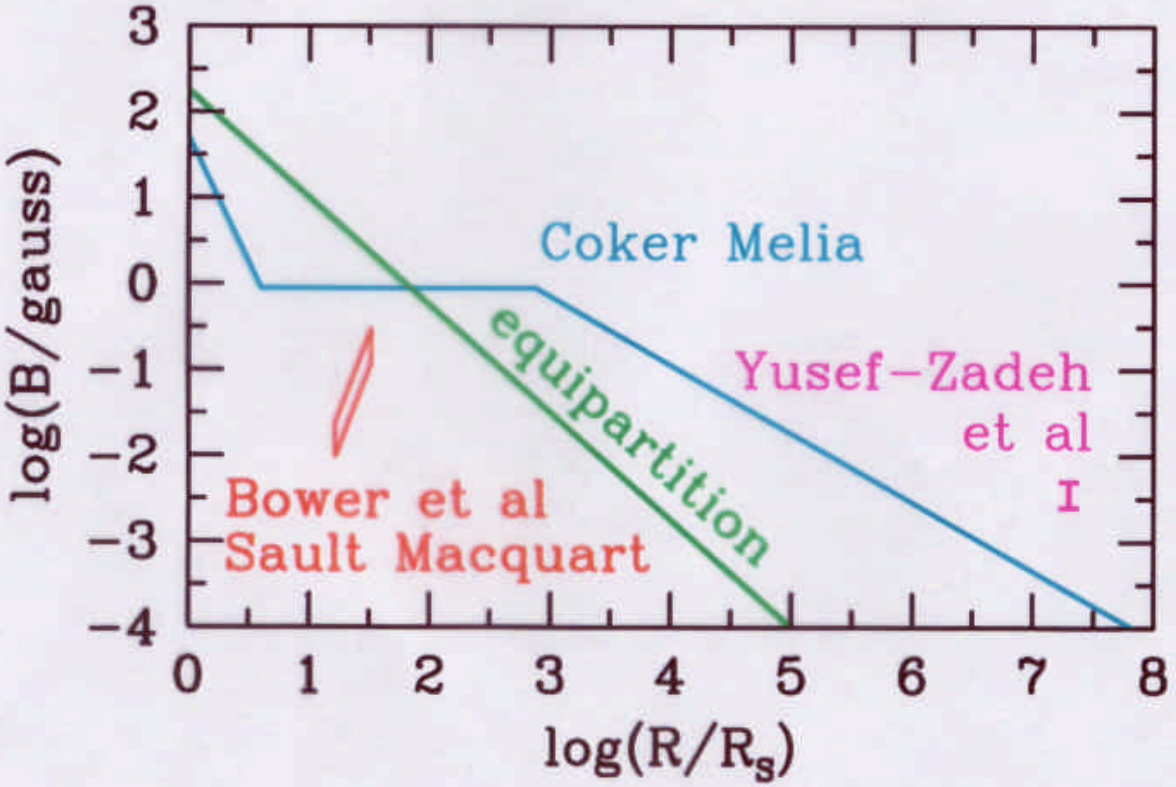
Gondolo, Silk 1999-2000

*No signals $\Longrightarrow$ upper limit on inner halo slope $\gamma$*



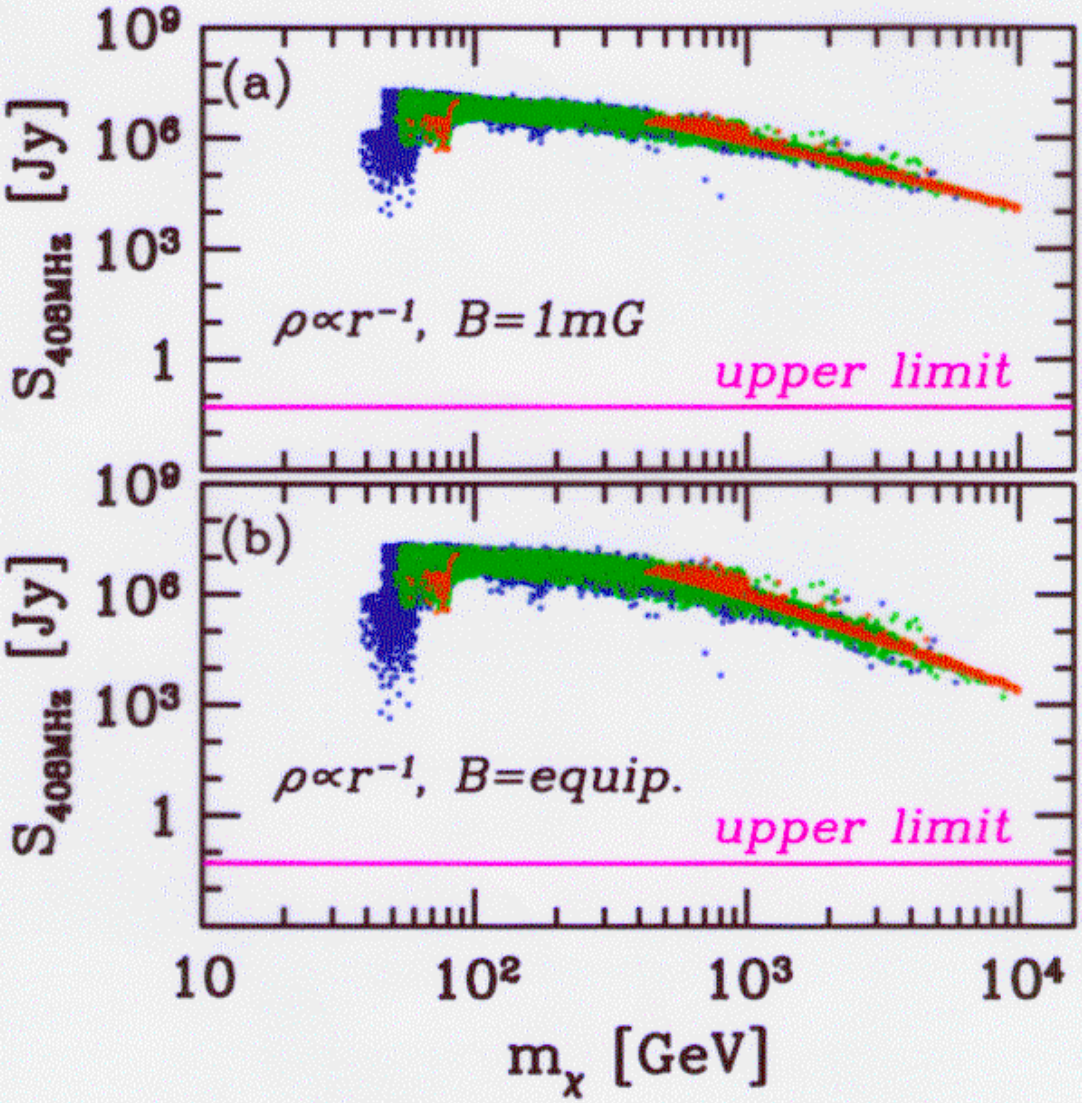
# Magnetic field around Sgr A*

- few milligauss at $\sim 5$ pc (Zeeman splitting in OH emission)
- tenths of a milligauss at $\sim 20\ R_S$ (circular polarization)
- accreting plasma carries magnetic field



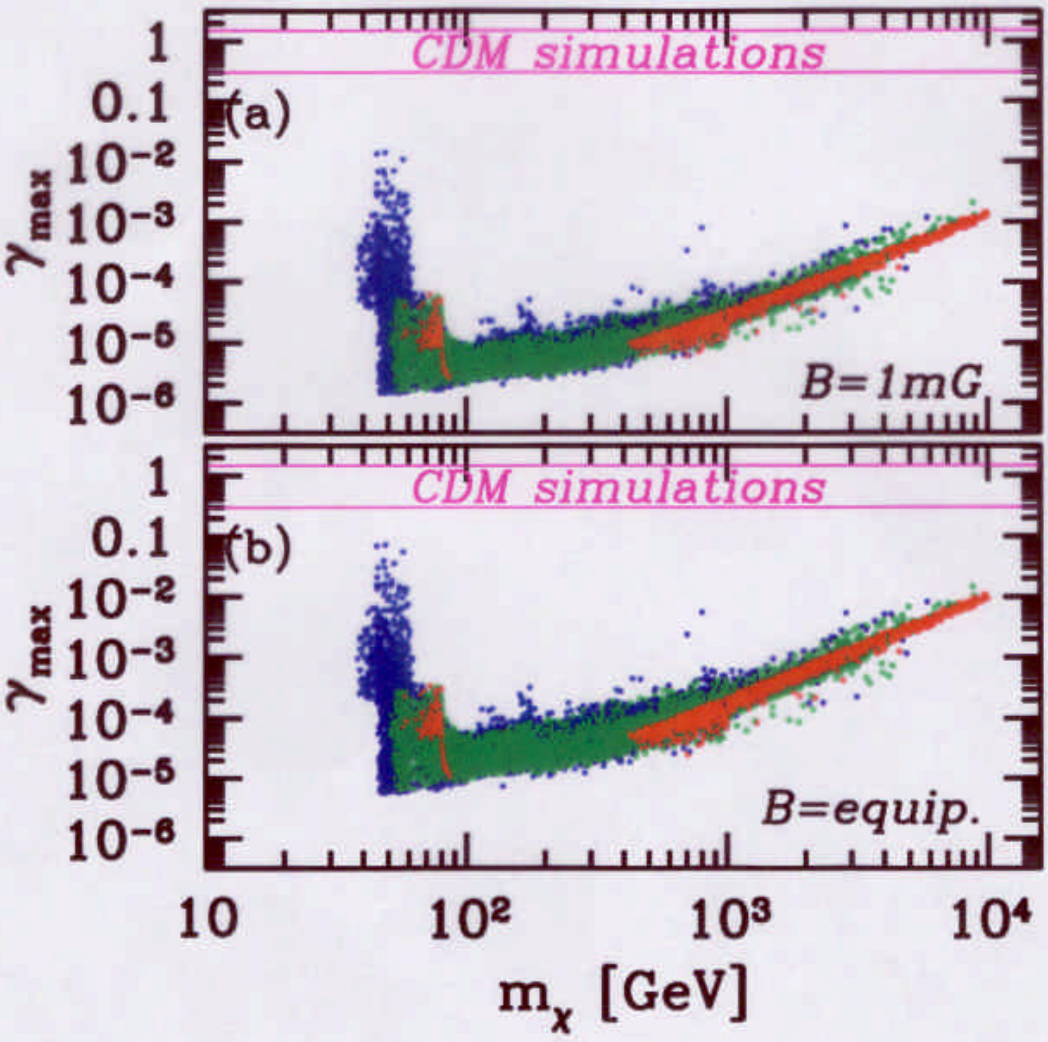
# If the dark halo is cuspy, dark matter is not neutralinos

**Gondolo 2000**



# If dark matter is neutralinos, the dark halo is not cuspy

**Gondolo 2000**



# Summary

- neutrinos from Sun/Earth
  - looking forward to a $km^3$ detector
- cosmic rays from galactic halo
  - $\gamma$: spectral signatures, fluxes depend on halo model
    $e^+$: right spectrum but low intensity
    $\overline{p}$: uncertain astrophysical fluxes
  - many experiments to come (VERITAS, MAGIC, AMS, PAMELA, ...)
- neutrinos, gamma-rays, and radio waves from galactic center
  - new adventure