Hot on the Trail of Particle Dark Matter: Indirect Searches

Dan Hooper

University of Oxford

- Gamma-Ray Experiments

  -Ground Based: HESS, Whipple, Veritas,...

  -Satellites: Revisiting EGRET

- Anti-Matter Experiments

  -The HEAT Positron Excess

  -Future Anti-Matter Experiments: PAMELA, AMS-02

- Neutrino Telescopes

  -AMANDA, ANTARES, IceCube

  -Limitations and Possibilities

How To Search For a WIMP?

- Collider Searches

  -If $m_X \sim m_{EW}$, and $\sigma \sim g^4/m_X^2$,

  Detection very likely in future colliders

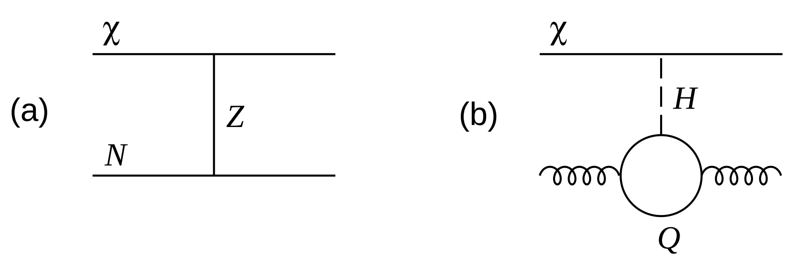
  -Strong constraints from existing LEP data

- Direct Detection

  -If $m_X \sim m_{EW}$, and $\sigma \sim g^4/m_X^2$,

  Naively expect, $\sigma_{XN} \sim G^2 \frac{m_N^2 m_X^2}{(m_N+m_X)^2}$ via Z-exchange (axial-vector)

  And, $\sigma_{XN} \sim G^2 \frac{m_N^2 m_X^2}{(m_N+m_X)^2} \frac{m_N^2}{m_W^2}$ via h-exchange (scalar)



  -Can be highly suppressed, however

  -CDMS, Edelweiss, Zeplin provide tightest current bounds

How To Search For a WIMP?

- Indirect Detection

  -If $m_X \sim m_{EW}$, and $\sigma \sim g^4/m_X^2$,

  Dark matter annihilations may provide observable fluxes of:

  1) gamma-rays from the Galactic Center or Galactic substructure

  2) neutrinos from the Sun

  3) positrons from the local halo

  4) anti-protons or anti-deuterons from the Galactic Halo

  -However, we can write $< \sigma v > \simeq a + bv^2 + \mathcal{O}(v^4)$

  -If $a \sim b$ or $a >> b$, excellent prospects for indirect detection

  -If $a << b$, present annihilations suppressed by $\sim (10^{-3})^2$

SUPERSYMMETRY

- The Minimal Supersymmetric Standard Model (MSSM)

  -New superpartner for each Standard Model particle: sleptons, squarks, neutralinos and charginos

  -Requires 5 Higgs bosons (2 Higgs doublets)

  -Numerous ways to break supersymmetry

  -Parameterized by over 100 free parameters

- R-Parity Conservation

  -Introduced to avoid fast proton decay

  -Defined as $R = (-1)^{3B+L+2s}$

  $\rightarrow$ +1 for all SM particles and -1 for all superpartners

  -Insures that the Lightest Supersymmetric Particle (LSP) is stable

- Neutralino Properties

  -Lightest neutralino likely LSP

  -Properties derive from 4x4 neutralino mass matrix

  -Depends only on $M_2, \mu, \tan\beta, (\mathrm{M}_1)$

  -Diagonalization determines masses, composition and couplings

- Relic Density

  -A neutralino LSP can naturally provide the measured relic density

Gamma-Rays From The Galactic Center

- Annihilation Region
  -Dark matter can exist in high densities near the galactic center
  -Large annihilation rates provide large gamma-ray fluxes
- Current ACT Observations
  -HESS
  -Whipple 10 meter telescope
  -CANGAROO-II
- Satellite Observations
  -EGRET
  -A source or only a limit?
- Evidence of Dark Matter?
  -Spectral features
  -Required annihilation rate, mass
  -Possible astrophysical sources

GAMMA-RAY SPECTRAL FEATURES

- Line Emission

  -No tree level photon final states for SUSY, Kaluza-Klein DM

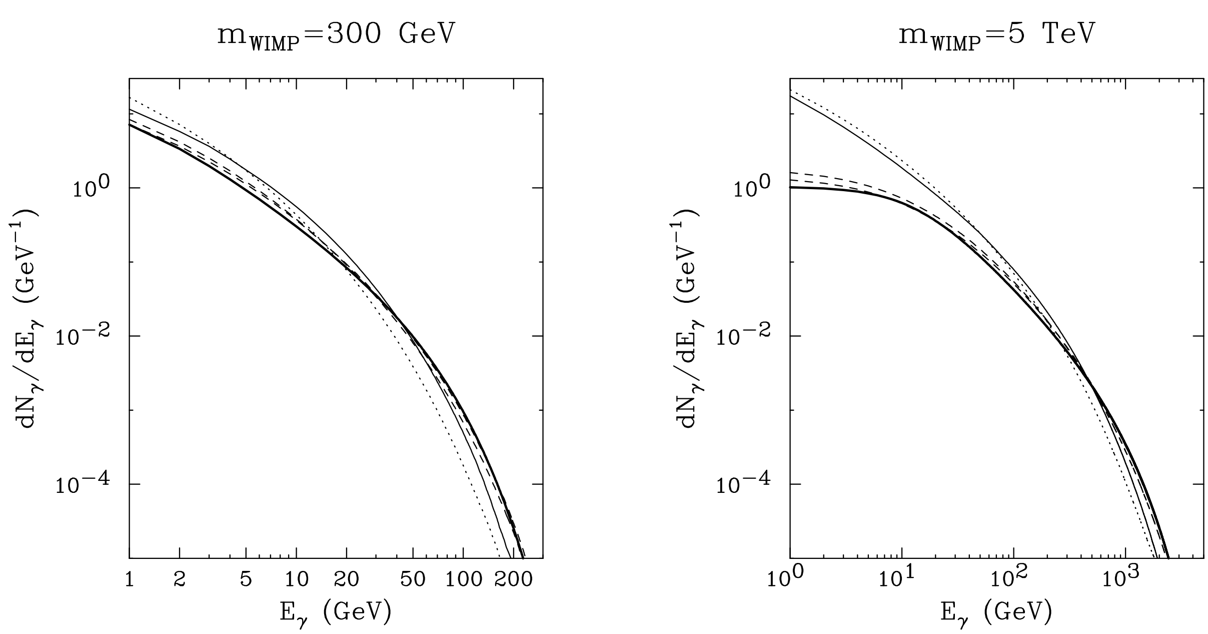
  -Loop diagrams to $\gamma\gamma$ and γZ

  -Smaller cross section, but distinctive features

- Continuum Emission

  -Annihilations to gauge bosons, quarks, leptons, etc. contribute

  -Typical energies much lower than WIMP mass



GAMMA-RAY SPECTRUM: BEFORE HESS

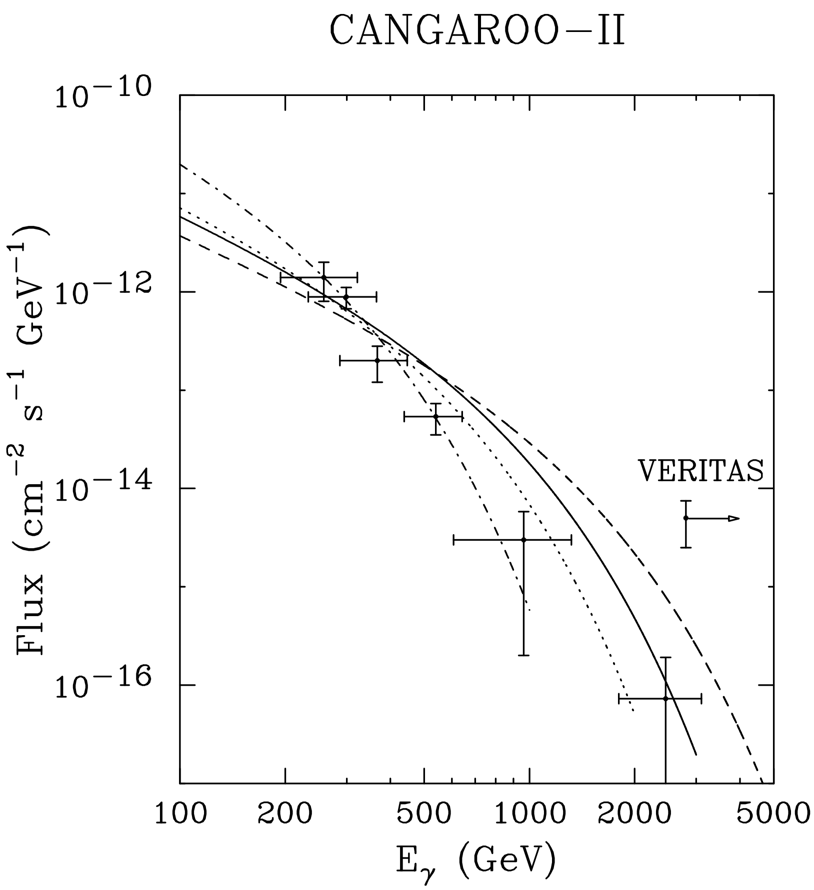
- CANGAROO-II Observation

  -Spectrum consistent with 1-3 TeV annihilating particle

- Whipple Observation

  -Substantial flux *above* 2.8 TeV

  -Difficult to reconcile with CANGAROO-II



(Hooper, *et al.*, JCAP, astro-ph/0404205)

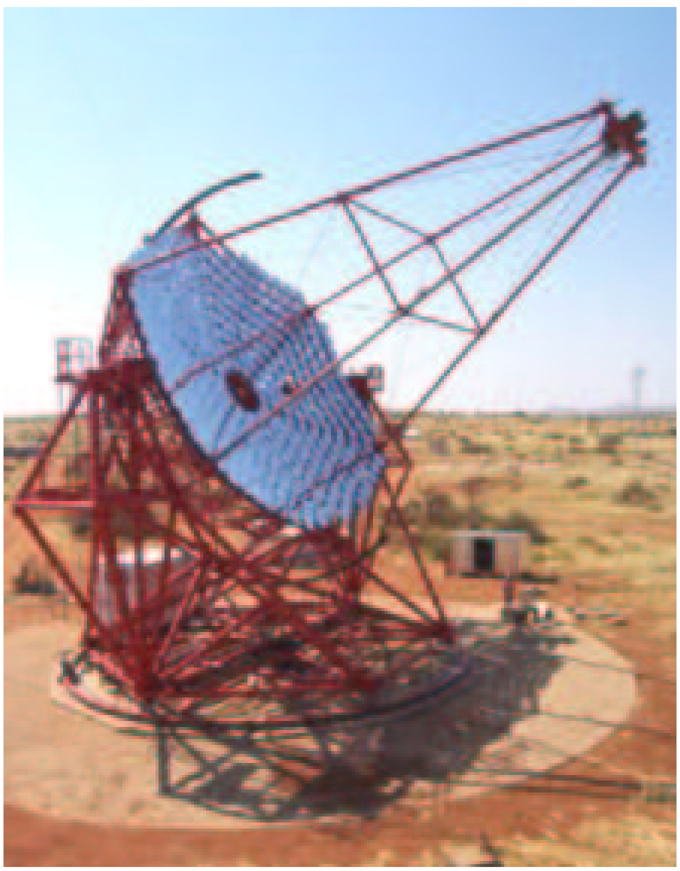
And Then There Was HESS...

- The HESS Telescope

  -Array of 4 ACTs

  -Southern Hemisphere Location (Namibia)

  -Superior Spectral *and* Angular Resolution



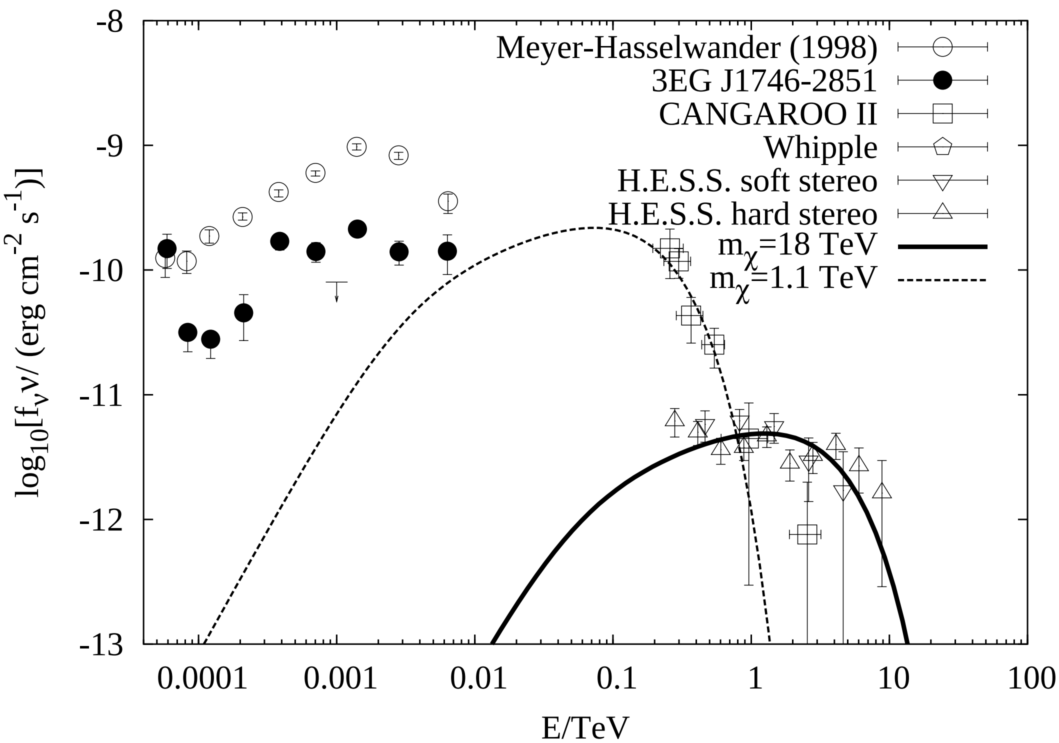
Gamma-Ray Spectrum: After HESS

▶ HESS Observation

-Spectrum Extending to $\sim$ 10 TeV

-Very different from Cangaroo-II spectrum

-Roughly consistent with Whipple



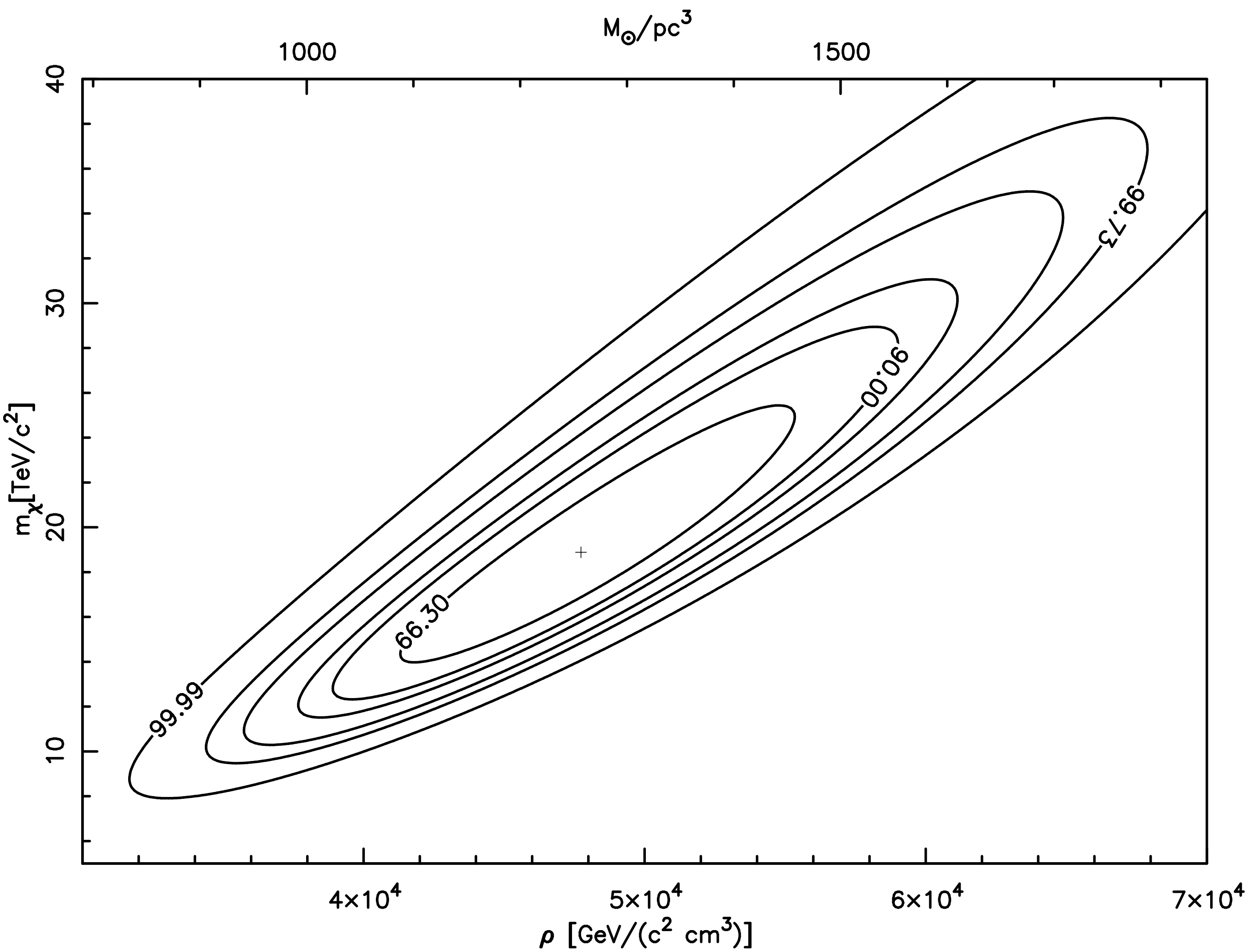
(D. Horns, astro-ph/0408192)

Gamma-Ray Spectrum: After HESS

- Dark Matter Characteristics

  -Requires 10-40 TeV mass

  -Well outside of range generally favored



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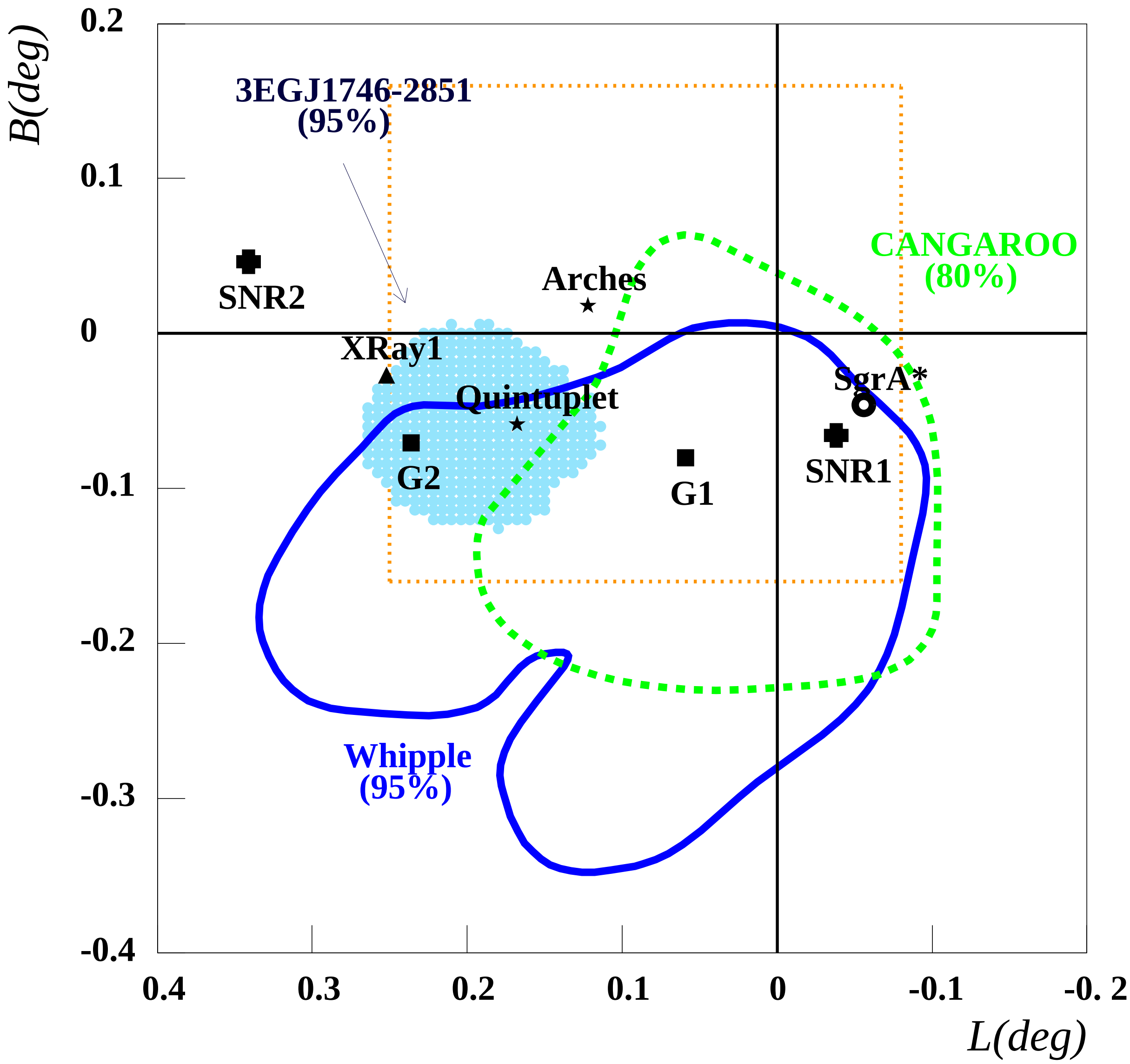
Location, Location, Location

▶ Before HESS

-Ambiguity in Source Location(s)



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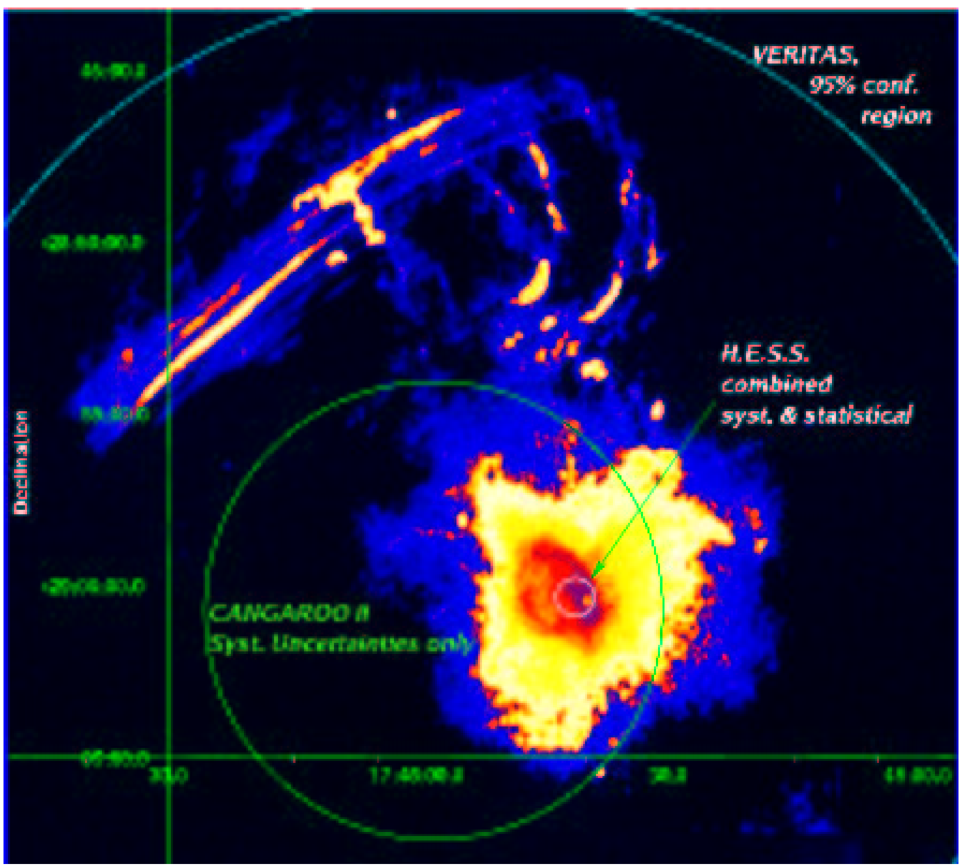
LOCATION, LOCATION, LOCATION

- ▶ After HESS

  -Precise angular resolution

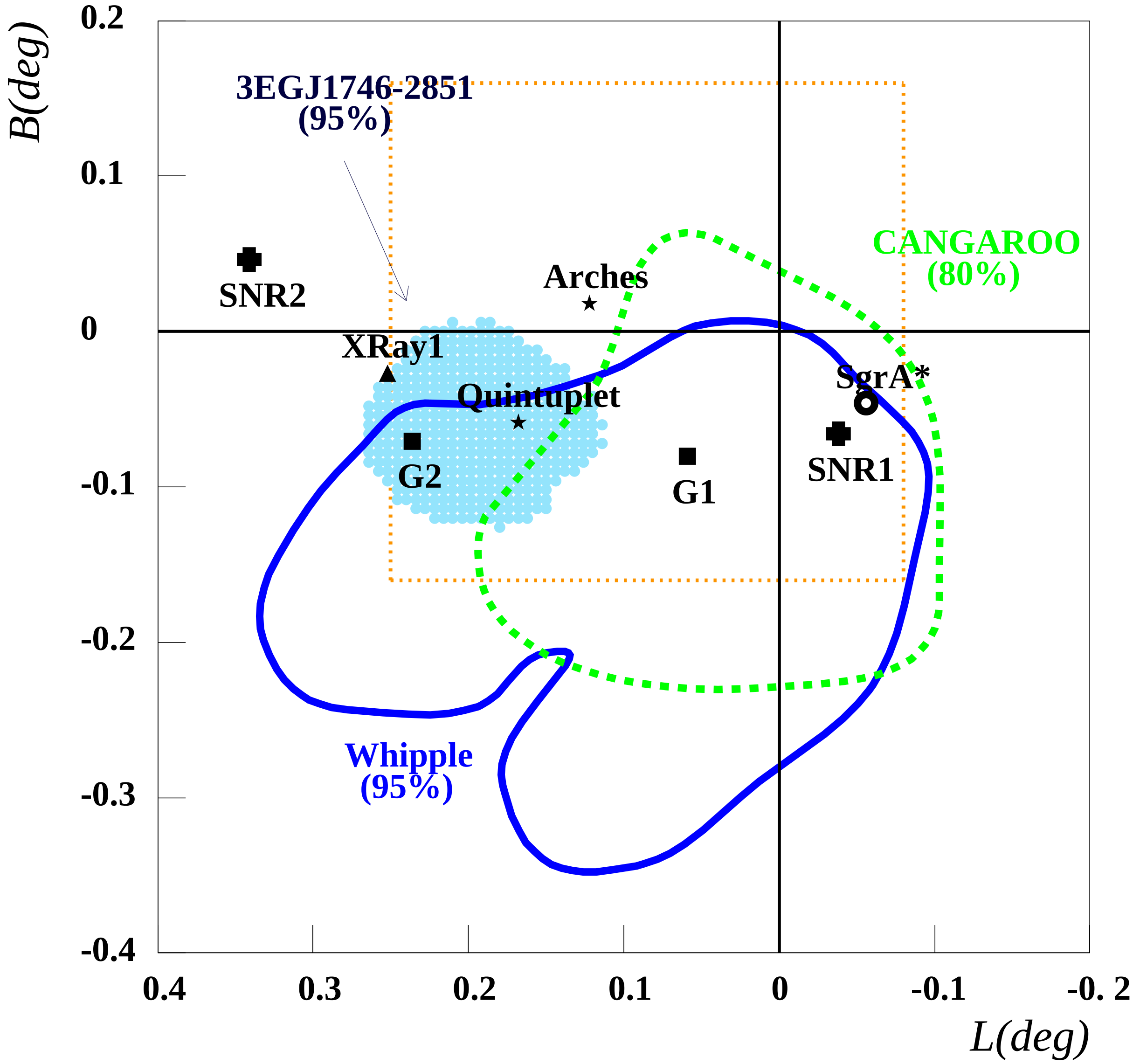
  -Leaves only Sgr A* and SNR1 as possible sources



(D. Horns, astro-ph/0408192)

THE EGRET SOURCE

- Does EGRET see the same source?



THE EGRET ANALYSIS

- EGRET: The Energetic Gamma Ray Experiment Telescope

  -Launched on the Compton Gamma Ray Observatory in 1991

  -Sensitive To gamma rays between 30 MeV and 30 GeV

  -Accumulated an exposure of $\simeq .2 \times 10^{10}\,\mathrm{cm}^2\,\mathrm{sec}$ of the galactic center region

- Galactic Center Source?

  -Original EGRET analysis: single point spread function and 0.5° bins

  -$\rightarrow$ Flux found of $\sim 10^{-7}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ above 1 GeV, consistent with GC

  -Dingus/Hooper analysis: energy dependent point spread function and unbinned technique

  -$\rightarrow$ Source of flux 0.2° off-center, excluded from GC beyond 99.9%

  -$\rightarrow$ Limit from GC of $10^{-7} - 10^{-8}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

  -Consistent with HESS

(Hooper and Dingus, PRD (in press), astro-ph/0210617)

A Signal of Dark Matter?

- Gamma-Ray Flux
  $\Phi_\gamma(\psi, E_\gamma) = \langle\sigma v\rangle \frac{\mathrm{dN}_\gamma}{\mathrm{dE}_\gamma} \frac{1}{4\pi M_X^2} \int_{\mathrm{los}} \mathrm{dl}(\psi)\, \rho^2(\mathrm{r})$

  Break down Into 2 factors:

  1) halo characteristics

  2) particle physics

- Halo Factor
  $J(\psi) = \frac{1}{8.5\,\mathrm{kpc}} \left(\frac{1}{0.3\,\mathrm{GeV/cm}^3}\right)^2 \int_{\mathrm{los}} \mathrm{dl}(\psi)\, \rho^2(\mathrm{l})$

  -Value of $J(\Delta\Omega)$ highly uncertain

Halo Models

- Cuspy Halo Models

  - N-body simulations favor cusped halo models, $\rho \propto 1/r^{\gamma}$, $\gamma \sim 1.2$

  -Includes Navarro, Frenk, White (NFW), and Moore *et.al.* profiles

  -$J(5 \times 10^{-5}\,\mathrm{sr}) \sim 10^4$ to 10^6

  -With 10 arcminute resolution, appears as point source

- Core Halo Models

  -Some observations favor models with flat cores, $\gamma \sim 0$

  -Not dense enough to observe dark matter annihilation

  -Produces extended annihilation signal

- Other Effects

  -Adiabatic compression $\rightarrow J(5 \times 10^{-5}\,\mathrm{sr}) \sim 10^6$ to 10^8

  -Adiabatic accretion onto SMBH $\rightarrow$ density spike, $\gamma \simeq 2.4$

A Signal of Dark Matter?

- Dark Matter Requires:

  1) Very heavy particle ($\sim$ 20 TeV)

  AND

  2) Large annihilation cross section

  AND

  3) Extremely dense inner halo (spikes, adiabatic compression, etc)

- Astrophysical Alternatives

  1) Acceleration associated with SMBH (several possibilities)

  2) Nearby supernova remnant too near to rule out

(See: Aharonian and Neronov, astro-ph/0408303; Atoyan and Dermer, astro-ph/0410243)

DARK MATTER CANDIDATES

- Non-Baryonic Candidate Zoo

  neutralinos

  Kaluza-Klein excitations

  theory-space little Higgs dark matter

  massive neutrinos

  sterile neutrinos

  axions

  light scalar particles

  sneutrinos

  axinos

  gravitinos

  Q-balls

  Superweakly Interacting Massive Particles (SuperWIMPs)

  mirror particles

  D-matter

  WIMPZILLAS!

  CHArged Massive Particles (CHAMPs)

  Shadow World Matter

  Brane World Dark Matter

  Cryptons

  etc.

  ... and this was only after 10 minutes of searching on the arXiv!

MESSENGER DARK MATTER

- Gauge Mediated Supersymmetry Breaking

  -Supersymmetry is broken in ~ 100 TeV sector

  -Messengers communicate SUSY breaking through gauge couplings

  -LSP is a light gravitino (1-10 eV)

- Messenger Particles

  -Lightest messenger particle can be stable

  ~ 10 TeV scalar neutrino natural dark matter candidate

Hooper and J. March-Russell, hep-ph/0412048
See also, Dimopoulo, Giudice and Pomarol, PLB, hep-ph/9607225,
Han and Hempfling, PLB, hep-ph/9708264

MESSENGER DARK MATTER

- Messenger Particles

  -Phenomenological problems present in minimal SUSY model

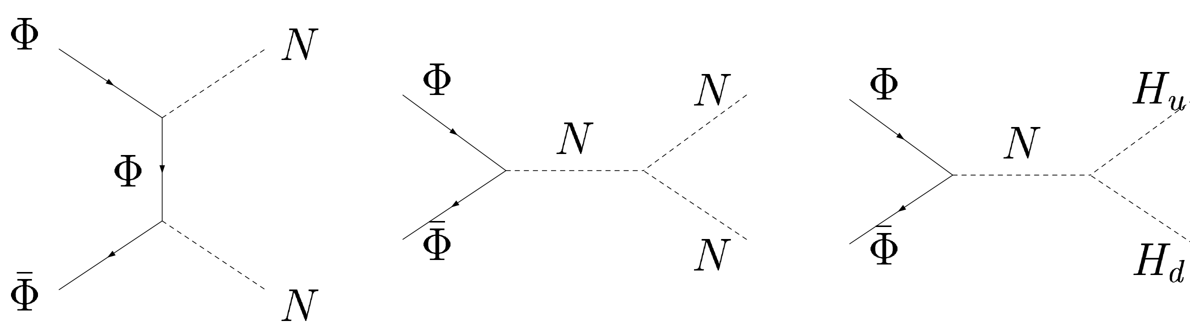
  -Consider model with additional Higgs singlet (NMSSM inspired)

- Messenger Annihilations

  -Potential includes the terms:

  $V = (4\xi_S\xi_N - 2\xi_N\eta_N)SN\bar{\Phi}\Phi + 2\eta_N kSN^3 - 2\eta_N\lambda_N NSH_uH_d + ...$

  -Leads to the annihilation diagrams:



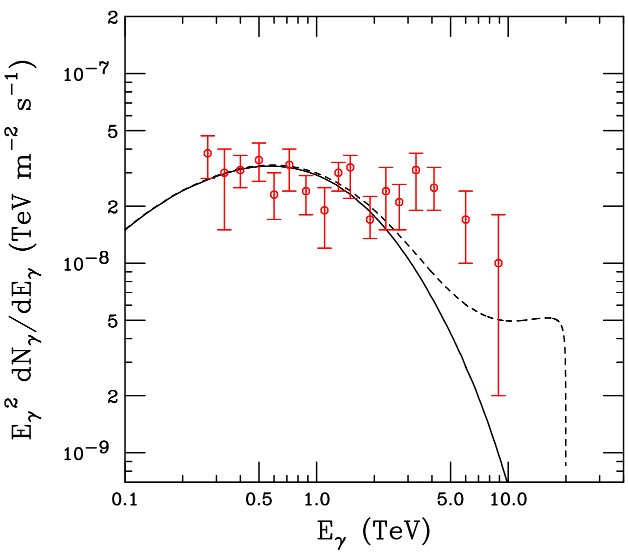
  -These diagrams are enhanced due to large $\langle S \rangle \sim 100$ TeV

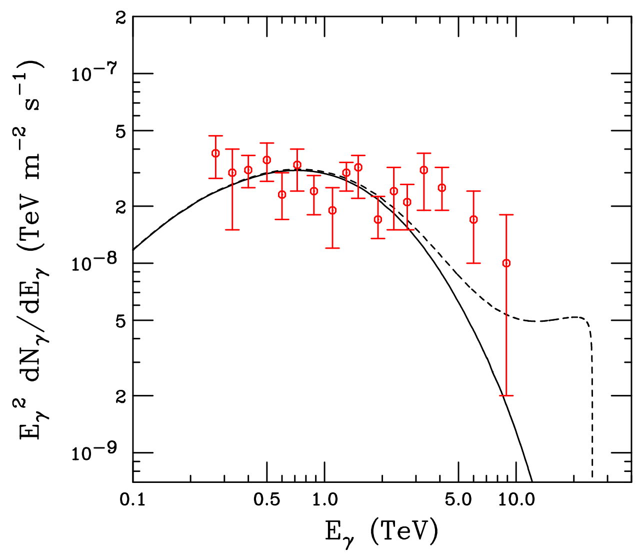
  -Yields observed dark matter density for $m_{\phi^0} \simeq 7$ to 25 TeV

Hooper and J. March-Russell, hep-ph/0412048
See also, Han, Marfatia and Zhang, PRD, hep-ph/9906508

Messenger Dark Matter

- Gamma-Ray Spectrum
  -Consistent with HESS results
  -Favors 20-25 TeV mass range





Hooper and J. March-Russell, hep-ph/0412048

COSMIC POSITRONS

- The Data

  -HEAT (1994,1995 and 2000) observed an excess of cosmic positrons

  -Peak occurs near 8 GeV, extending to at least 30 GeV

  -Difficult to explain with astrophysics

- Dark Matter?

  -Could annihilating dark matter explain the excess?

  -Required annihilation cross section?

  -(or) Local overdensity (dark clumps)?

The Positron Excess

- Positron Propagation

  -Move with random-walk through tangled interstellar magnetic fields

  -Lose energy via inverse Compton scattering (on starlight and CMB)

  -Resulting spectrum found by solving the diffusion-loss equation:

$$\frac{\partial}{\partial t}\frac{dn_{e^+}}{dE_{e^+}} = \vec{\bigtriangledown} \cdot \left[K(E_{e^+},\vec{x})\vec{\bigtriangledown}\frac{dn_{e^+}}{dE_{e^+}}\right] + \frac{\partial}{\partial E_{e^+}}\left[b(E_{e^+},\vec{x})\frac{dn_{e^+}}{dE_{e^+}}\right] + Q(E_{e^+},\vec{x})$$

- Choices/Ambiguities

  -Diffusion constant: both normalization and energy dependence

  -Energy loss rate: energy dependence known

  -Diffusion zone: less important

  -Halo profile: less important

  -Fit these quantities with cosmic ray data

SUPERSYMMETRY AND THE POSITRON EXCESS

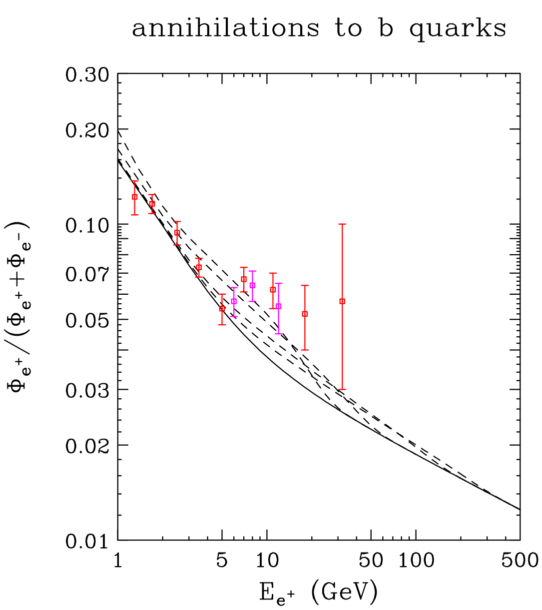
- Neutralino Annihilations

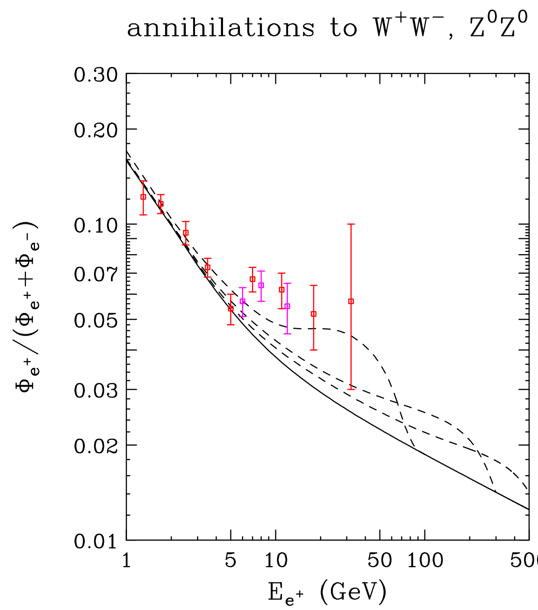
  -Gaugino-like: $b\bar{b}$, $\tau^+\tau^-$, $t\bar{t}$ dominate

  -Higgsino-like: Gauge and Higgs bosons dominate

  -Provide relatively soft spectra

  $\rightarrow$ requires fairly extreme diffusion parameters





Supersymmetry and the Positron Excess

- Neutralino Annihilation Rate

  -Annihilation modes inefficient positron production

  -Annihilation cross sections typically too small

  -Even with best-case SUSY models, “boost factors” of ~ 50 needed

  -Very unnatural quantities of dark substructure required

  ...Unless LSPs are generated non-thermally

(Hooper, Silk and Taylor, PRD, hep-ph/0312085)

Dark Matter Candidates

- Non-Baryonic Candidate Zoo

  neutralinos

  Kaluza-Klein excitations

  theory-space little Higgs dark matter

  massive neutrinos

  sterile neutrinos

  axions

  light scalar particles

  sneutrinos

  axinos

  gravitinos

  Q-balls

  Superweakly Interacting Massive Particles (SuperWIMPs)

  mirror particles

  D-matter

  WIMPZILLAS!

  CHArged Massive Particles (CHAMPs)

  Shadow World Matter

  Brane World Dark Matter

  Cryptons

  etc.

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UNIVERSAL EXTRA DIMENSIONS

- Universal Extra Dimensions
  -All particles propagate In bulk
  -Kaluza-Klein (KK) towers appear
  -KK number analogous to R-Parity
  -Lightest KK state stable
- The Lightest KK Particle
  -KK masses 1/R at tree level; Loop corrections determine spectrum
  -KK Hypercharge Gauge Boson, $B^{(1)}$, likely LKP
  -Similar to neutralino (LSP) in many respects
- Annihilation Cross Section

$$\sigma v = \frac{95 g_1^4}{324 \pi m_{B^{(1)}}^2}$$

Annihilates to: Charged Leptons $(60 - 70\%)$,
Up-type Quarks $(20 - 35\%)$,
Neutrinos $(3 - 4\%)$,
Remaining to down-type quarks and Higgs

ANNIHILATION CROSS SECTION OF THE LKP

- Relic Density Calculation

  -Ignoring coannihilations, $\Omega h^2 \simeq 0.1$ for $\sigma v \simeq 3 \times 10^{-26}$ cm^{3}s^{-1}

  -Corresponds to a mass of 800-1000 GeV

- With Coannihilations

  -Reasonable to expect several states near LKP mass

  -Coannihilations inefficient for depleting LKP density

  -Extra KK states eventually decay into LKPs

  $\rightarrow$ Increases LKP Relic Density

  -Smaller mass with larger cross sections plausible

(See, G. Servant and T. Tait, Nucl. Phys. B, hep-ph/0206071)

KALUZA-KLEIN DARK MATTER AND THE POSITRON EXCESS

- Positron Spectrum from KK Dark Matter

  -Annihilations to charged lepton pairs (60%)

  -Considerably harder positron spectrum than with SUSY

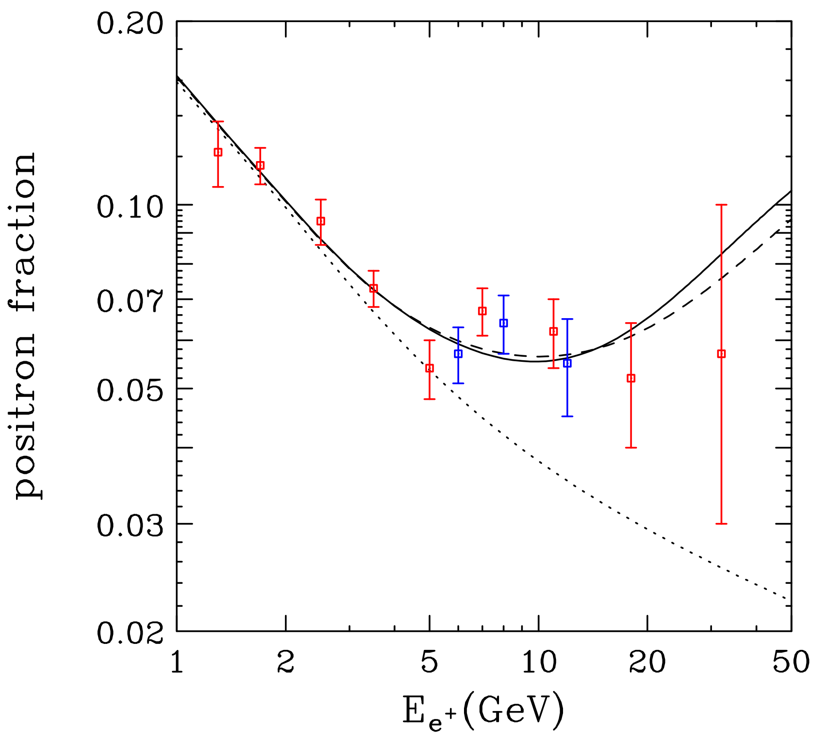
  -No substructure needed to fit spectrum

- Annihilation Rate

  -High annihilation rate: $\sigma v \simeq 0.6\,\mathrm{pb}/\mathrm{m}^2_{\mathrm{LKP}}(\mathrm{TeV})$

  -Coannihilations INCREASE relic density $\rightarrow$ higher σv

  -For $m_{\mathrm{LKP}} \simeq 300 - 400$ GeV, only modest boost factors required



(Hooper and G. Kribs, hep-ph/0406026)

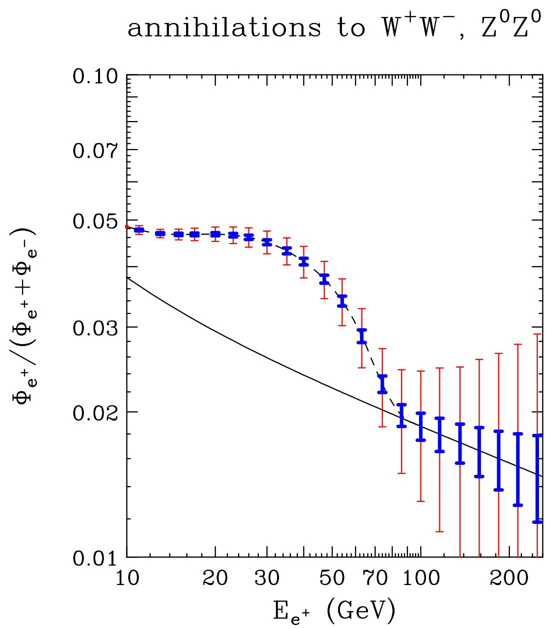
FUTURE PROSPECTS

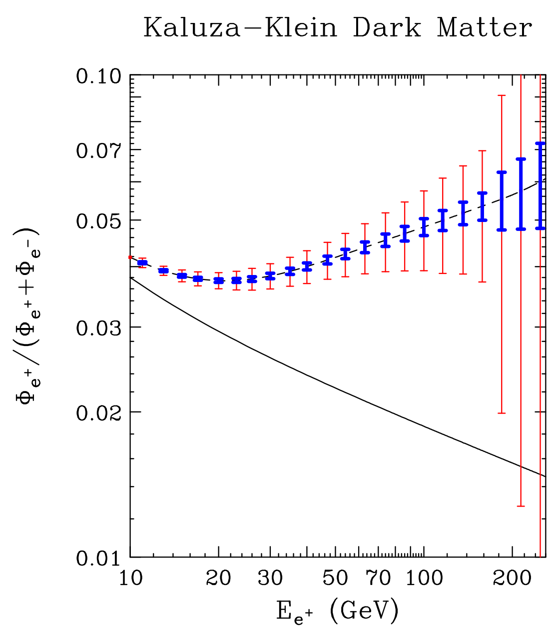
- Planned Experiments

  PAMELA (2005), AMS-02 (2008?)

  Sensitivity to $\sim 200\,\mathrm{GeV}$

  High Precision Measurements

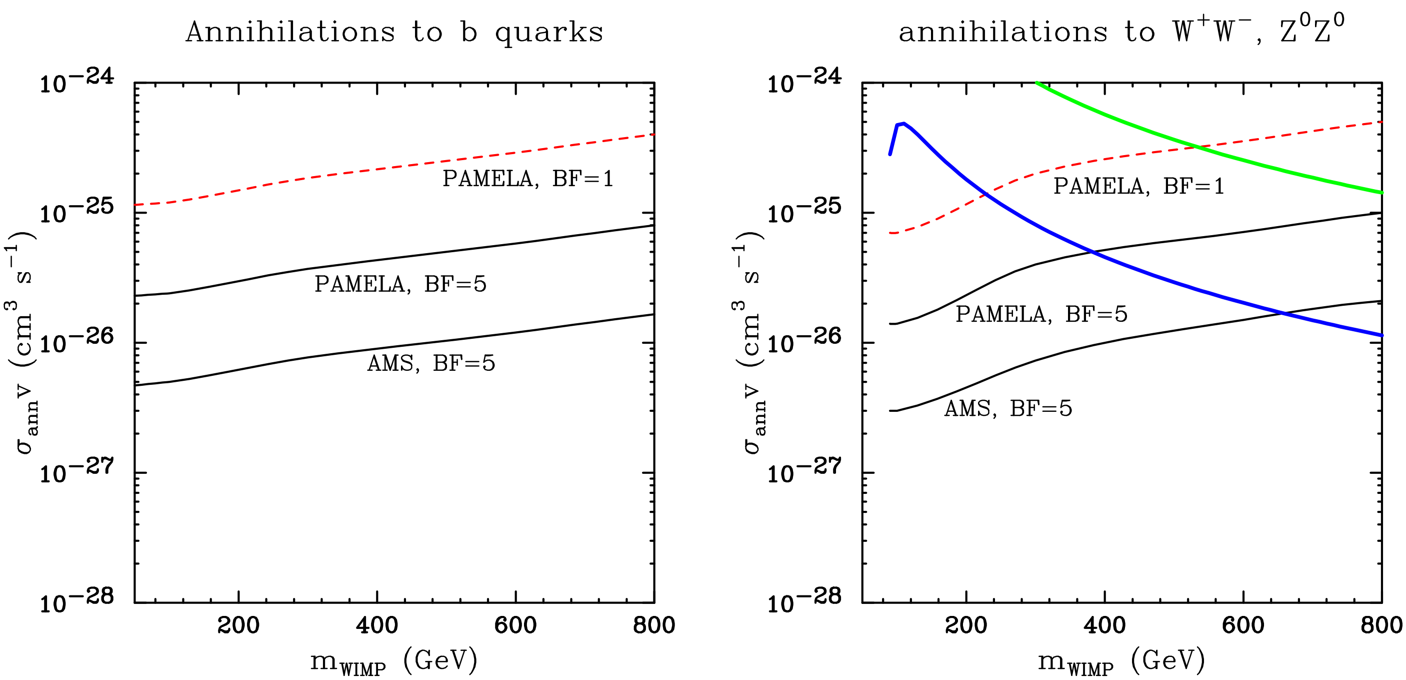




(Hooper and J. Silk, hep-ph/0409104)

FUTURE PROSPECTS

- Prospects for SUSY Dark Matter
  Depends on degree of local clustering (Boost Factor)
  and LSP composition (bino, wino, higgsino)

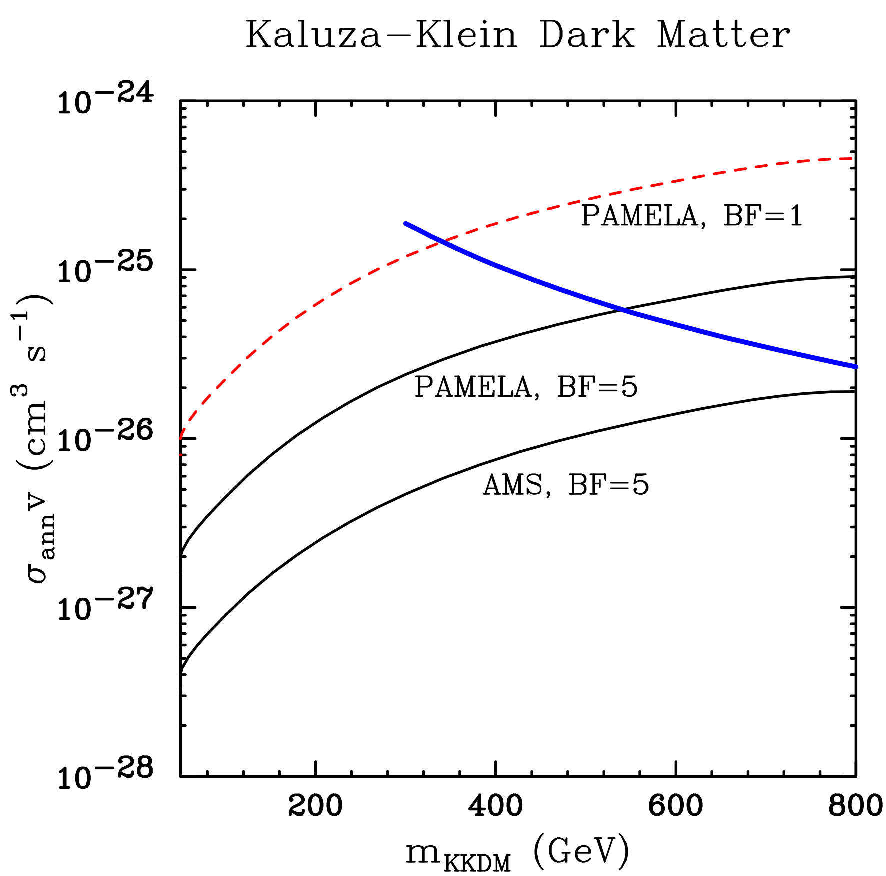


(Hooper and J. Silk, hep-ph/0409104)

FUTURE PROSPECTS

- Prospects for Kaluza-Klein Dark Matter

  Depends on degree of local clustering (Boost Factor)



(Hooper and J. Silk, hep-ph/0409104)

Neutrinos From The Sun

- The Process:

  -Halo dark matter scatter off nuclei in Sun/Earth

  -Many become gravitationally trapped $\rightarrow$ Annihilate in center

  -In Sun, annihilation rate can reach equilibrium with capture rate

  -Produces neutrinos via heavy quarks, gauge bosons, taus, (directly?)

  -Solar propagation/absorption are important effects

- Neutrino Telescopes

  -Square kilometer effective area: IceCube

  -Primary background: atmospheric neutrinos

  -Secondary background: neutrinos generated by cosmic rays in Sun

Neutrinos From The Sun

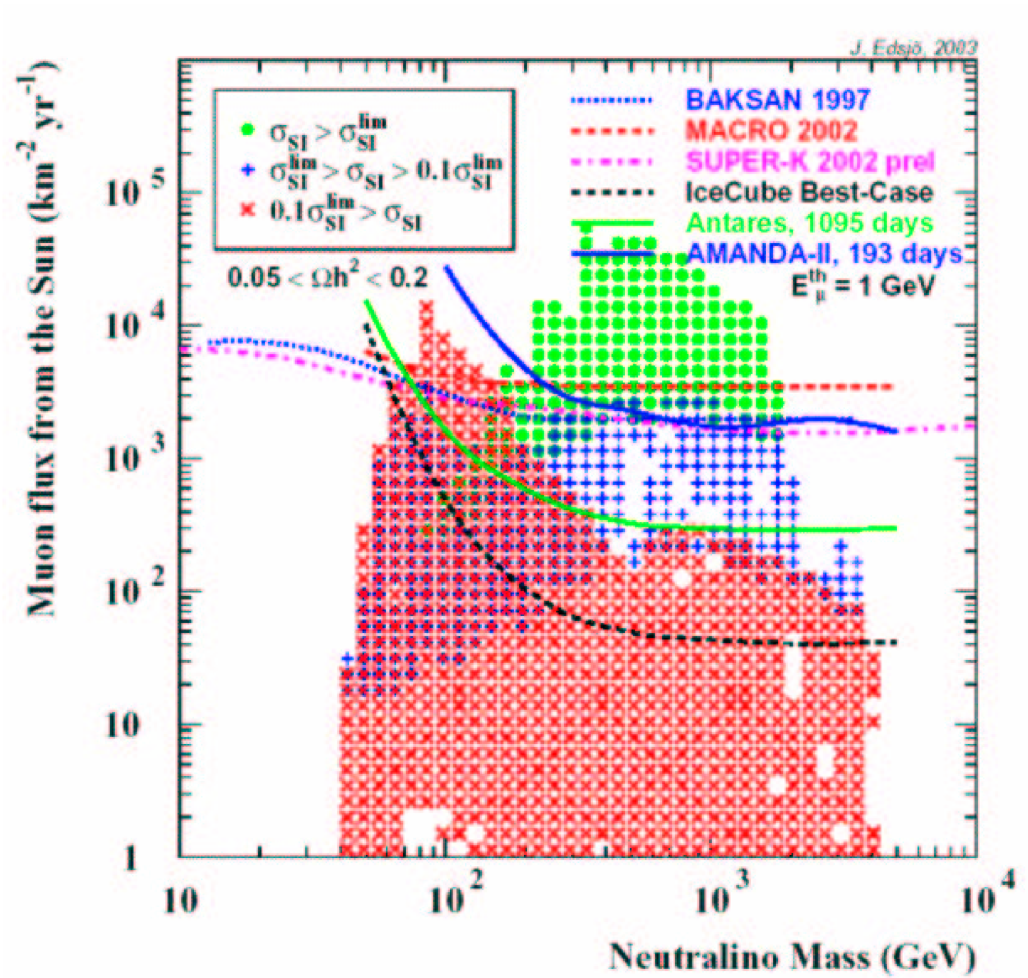
- Supersymmetry

  -Capture rate tied to direct detection rate

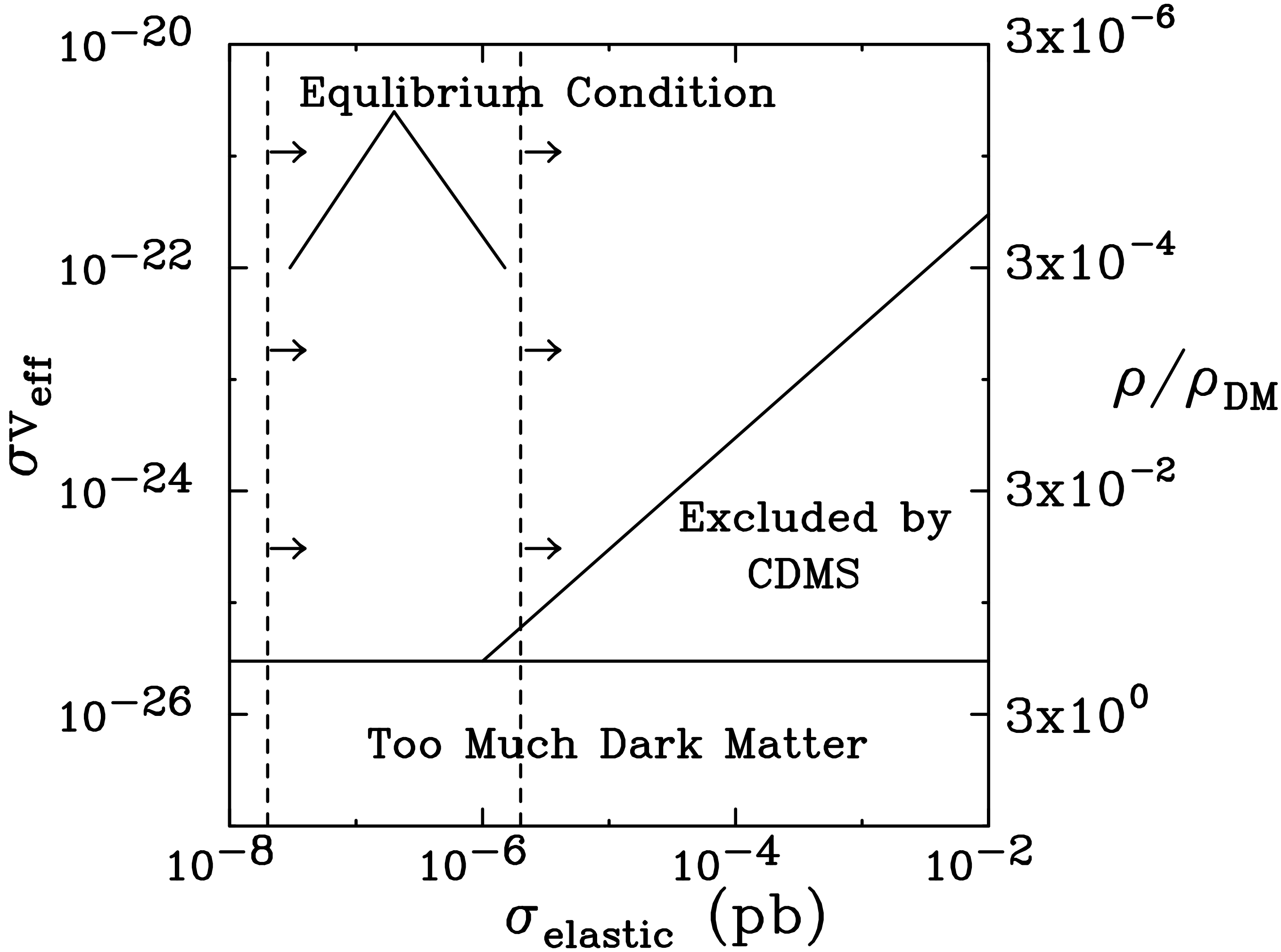
  -No direct annihilation to $\nu\bar{\nu}$

  -Flux dominated from $\tau^+\tau^-$, gauge bosons and heavy quarks

  -Low rates typical (excepting focus point region)



(Figure by J. Edsjo)



10−20
10−22
10−24
10−26
3x10−6
3x10−4
3x10−2
3x100
σveff
ρ/ρDM
Equlibrium Condition
Excluded by
CDMS
Too Much Dark Matter
10−8
10−6
10−4
10−2
σelastic (pb)

Dark Matter Candidates

- Non-Baryonic Candidate Zoo

  neutralinos
  Kaluza-Klein excitations
  theory-space little Higgs dark matter
  massive neutrinos
  sterile neutrinos
  axions
  light scalar particles
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  etc.
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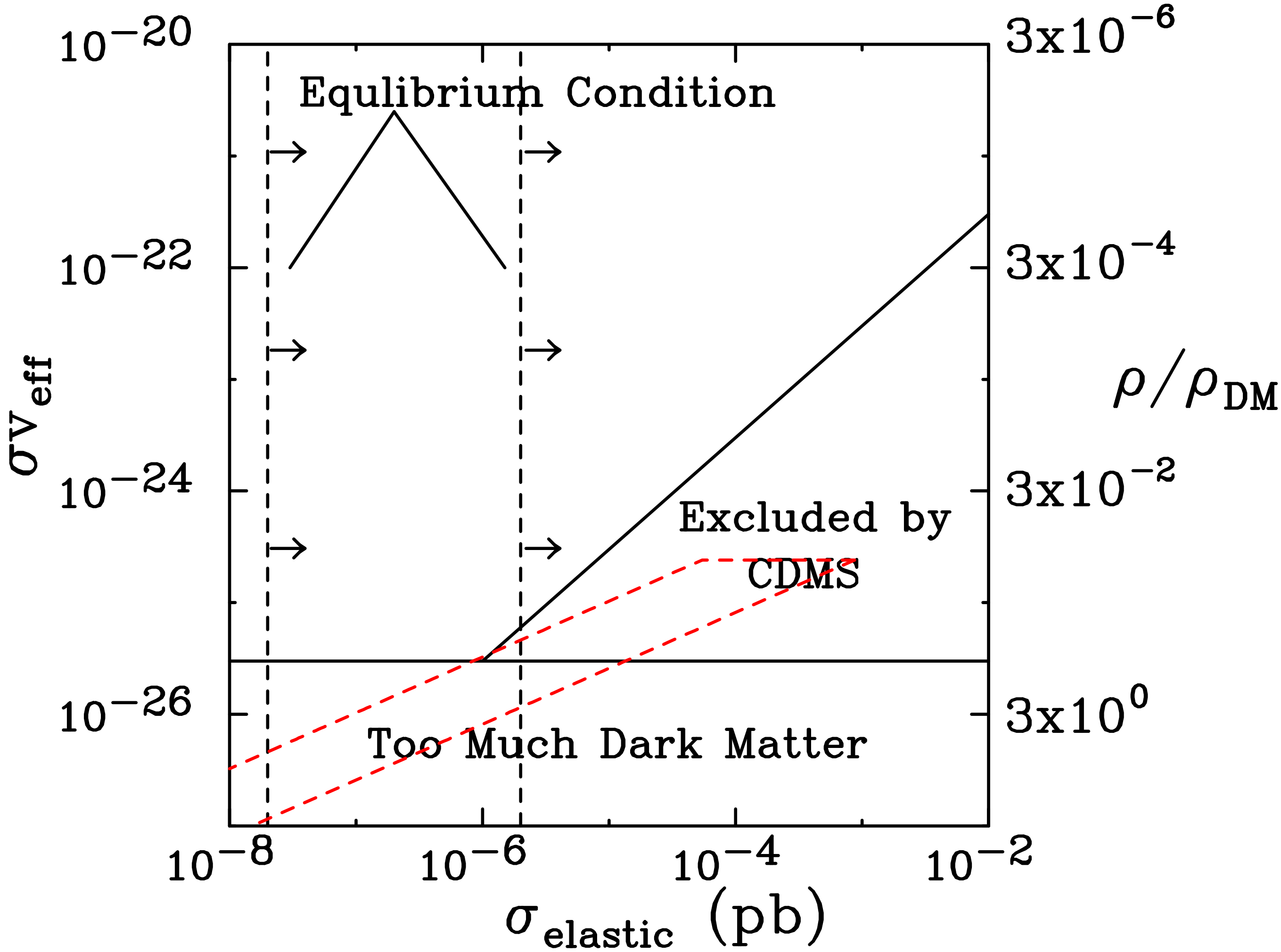
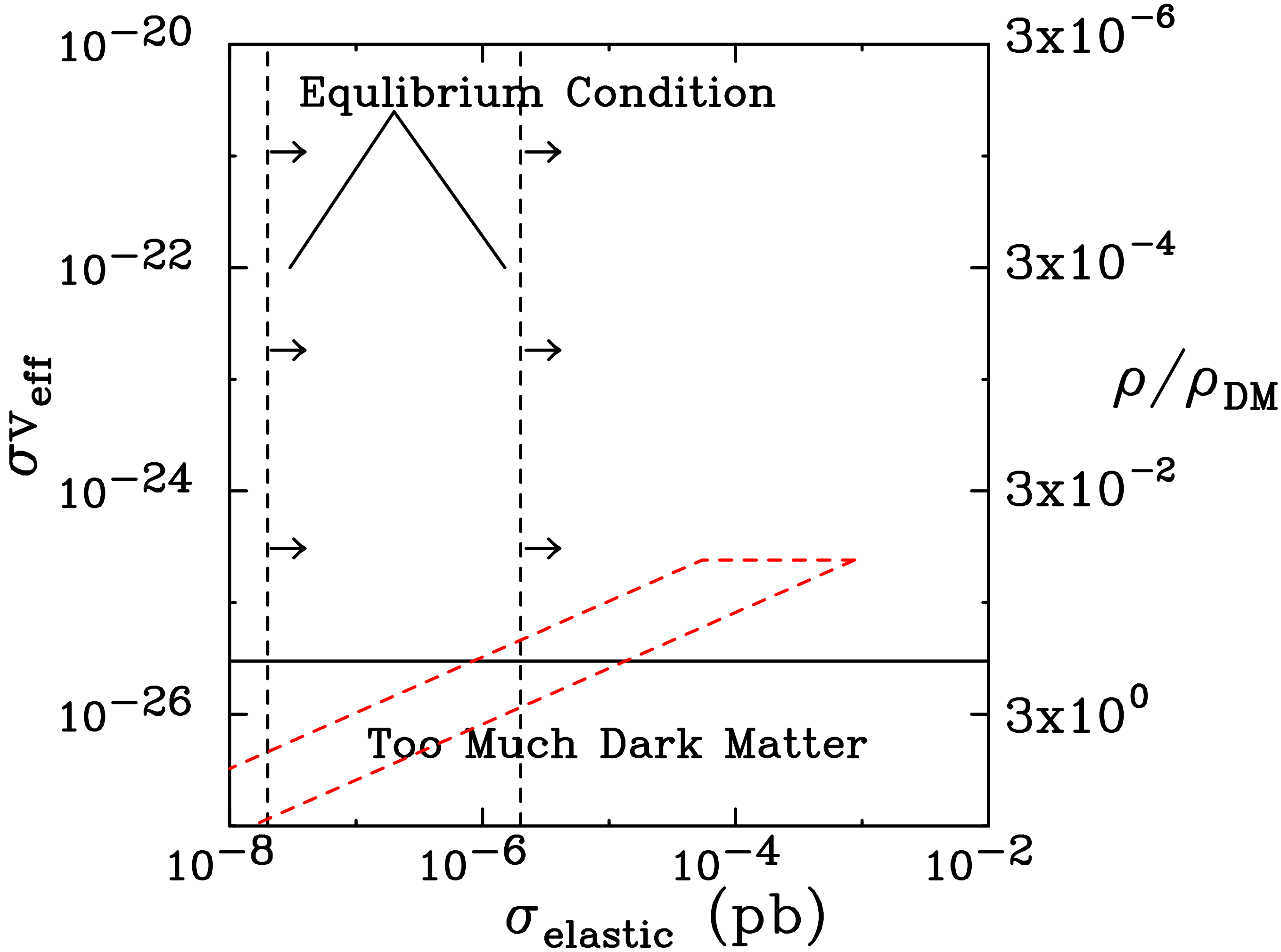
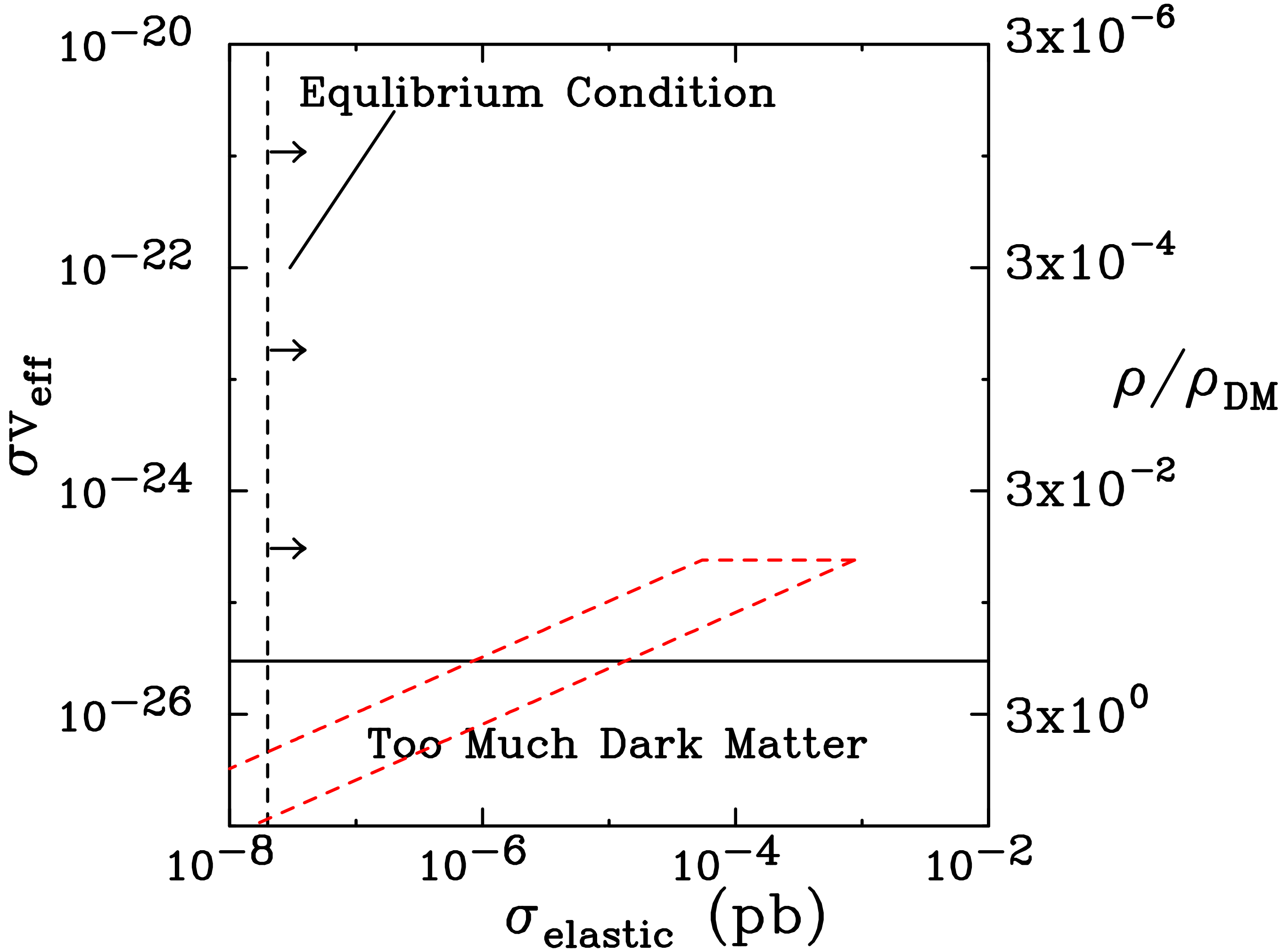
KALUZA-KLEIN DARK MATTER



KALUZA-KLEIN DARK MATTER

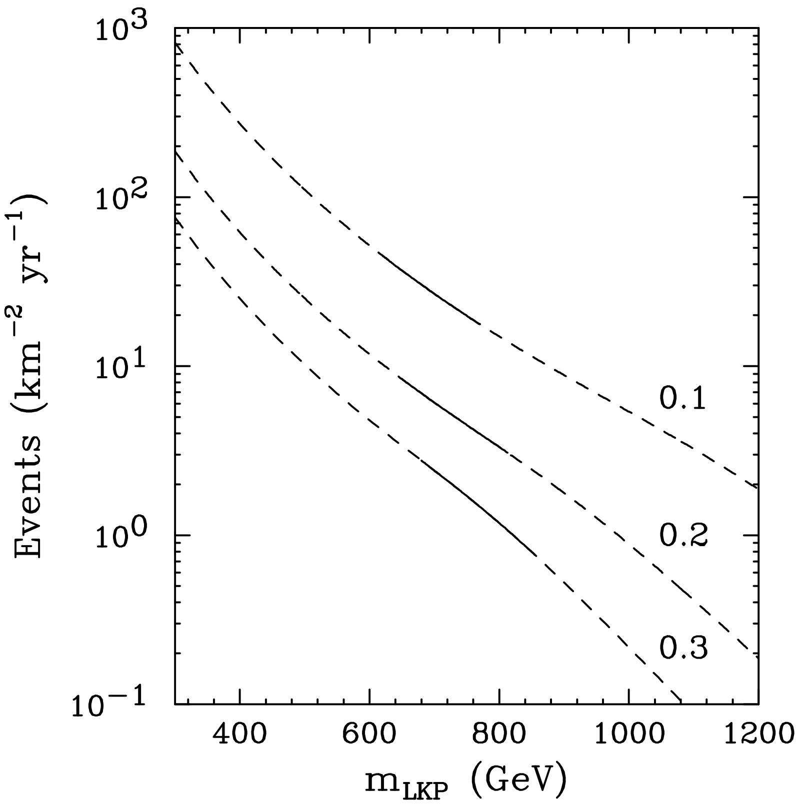


Kaluza-Klein Dark Matter



KALUZA-KLEIN DARK MATTER

- Annihilation Modes
  - -Direct annihilation to $\nu\bar{\nu}$ (3-4%)
  - -Flux dominated by $\tau^+\tau^-$ and $\nu\bar{\nu}$
  - -Significantly higher rates than neutralino dark matter
- Rate of Neutrino Induced Muons
  - -Depends on KK quark masses via capture rate
  - -Introduce parameter, $R = m_{q^{(1)}} - m_{\rm LKP}/m_{\rm LKP}$
  - -Results of loop calculations estimate $R \simeq 0.1 - 0.2$



(Hooper and Kribs, PRD, hep-ph/0208261)

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Sneutrinos Dark Matter

- Problems in the MSSM

  -Large elastic scattering cross section ($\sim 10^{-2}$pb)

  $\rightarrow$ Excluded by CDMS

  -Large annihilation cross section

  $\rightarrow$ Provides small fraction of total dark matter

- Model With Extra Singlet

  -Sneutrino+Scalar mixture is LSP

  -Elastic scattering and annihilation cross sections depleted

  -Motivated by a possible origin of neutrino masses

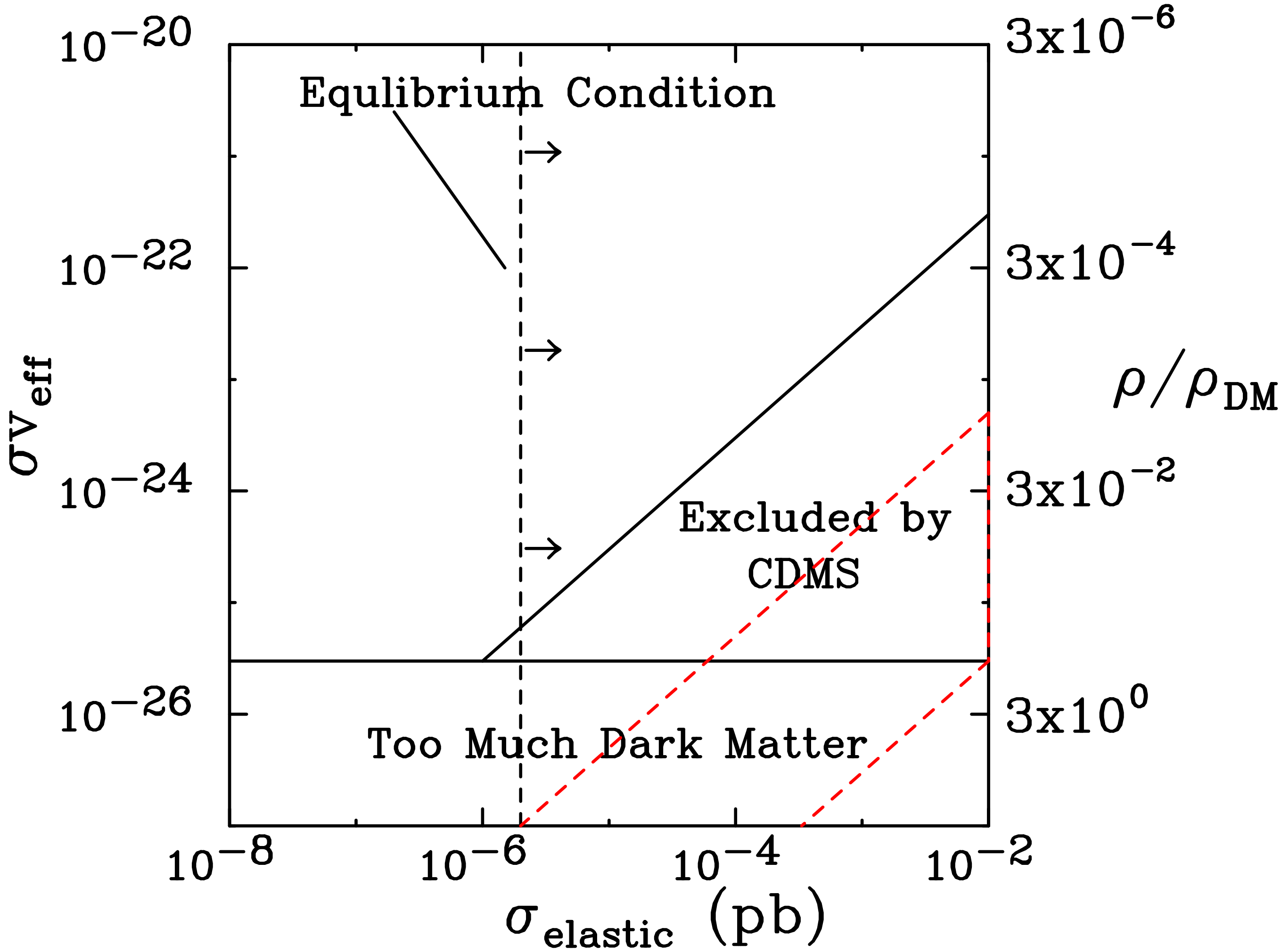
- Direct Detection

  -Only INELASTIC scattering with nucleons is allowed

  -Kinematics allow for consistency between CDMS and DAMA results

(See: Smith and Weiner, hep-ph/0402065 and PRD, hep-ph/0101138)

Mixed Sneutrino Dark Matter



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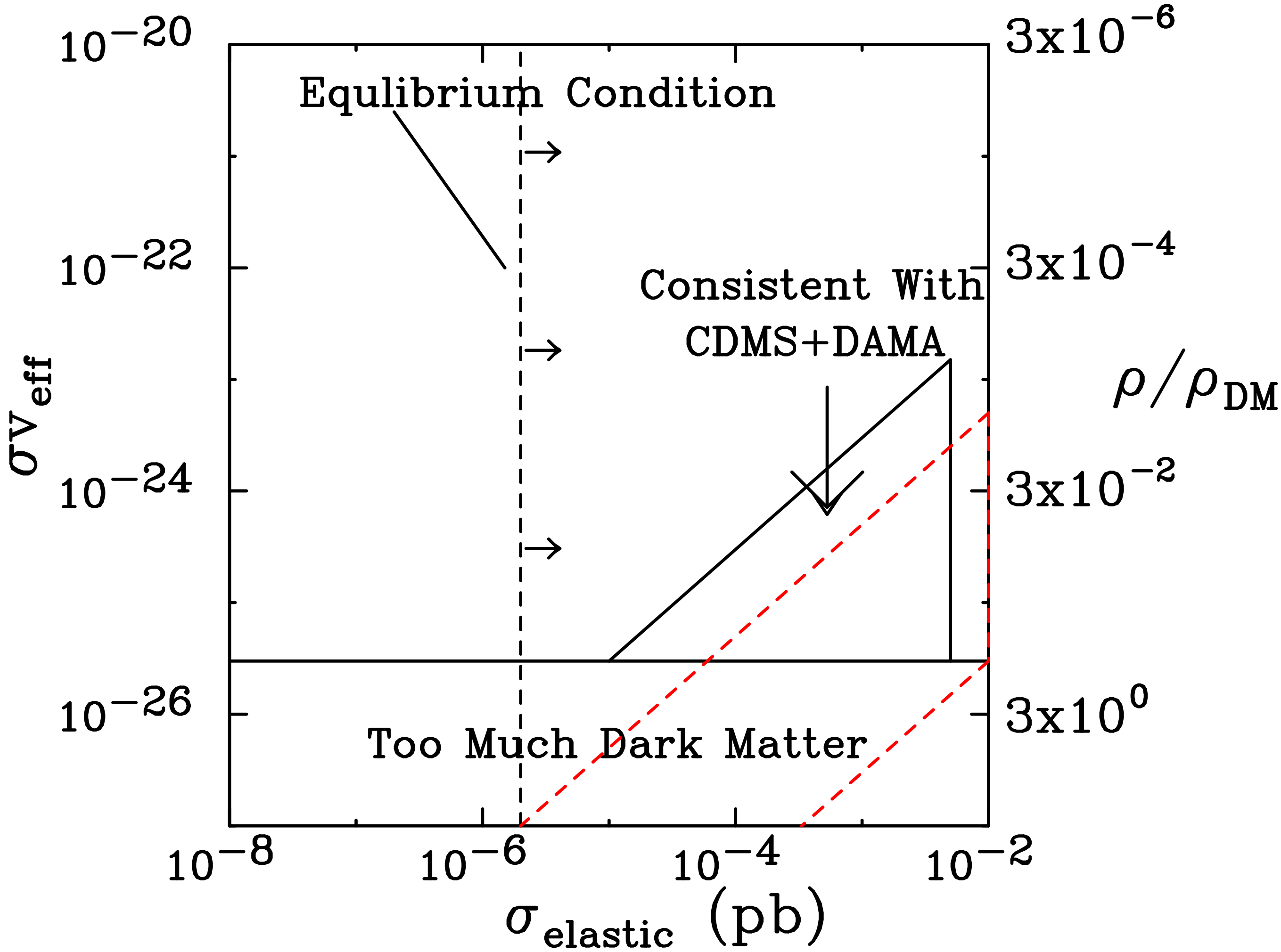

Mixed Sneutrino Dark Matter

- Light Mass Range ($m_{\tilde{\nu}} < 80$ GeV)

  ~99% of Annihilations to $\nu\bar{\nu}$

  $\rightarrow$ Perfect Dark Matter Candidate for Neutrino Telescopes!

  $\rightarrow$ Upward going muon rate up to $\sim 10^4$ per year in AMANDA

- Heavy Mass Range ($m_{\tilde{\nu}} > 90$ GeV)

  Annihilations to W^+W^-, Z^0Z^0

  $\rightarrow W^{\pm} \rightarrow l^{\pm}\nu$, $Z^0 \rightarrow \nu\bar{\nu}$

  $\rightarrow$ Upward going muon rate upto $\sim 10^3$ per year in AMANDA

Questions and Answers

- Many Questions...

  -Have ACTs Seen Signals of Annihilating Dark Matter?

  -Is the HEAT Excess the Product of Dark Matter Annihilations?

  -Can We Accommodate These Observations With "Reasonable" Particle Physics Models?

- Few Answers... Thus Far

  -Future Observations of Galactic Center: HESS, VERITAS

  -Future Anti-Matter Observations: PAMELA, AMS-02

- New Windows Soon To Open

  -Kilometer-Scale Neutrino Telescopes

  -Glast, Veritas, PAMELA, AMS-02

  $\rightarrow$ Will Extend Measurements to Far Greater Energies

  -Tevatron Currently Operating

  -LHC Turns on in 2007!

Three Possibilities

- Neutralino Dark Matter

  -The “vanilla” possibility – expected by many

  -Will not dramatically change anything

- Something More Exotic!

  -Kaluza-Klein states, GUT relics, etc...

  -Far more exciting that neutralino dark matter

  -Would represent a major turning point

  -Probably unlikely

- Undetectable Dark Matter

  -Gravitationally interacting, or otherwise hidden candidates

  -For those of us working in dark matter detection: God help us!

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