Dark Matter Models

Stephen West

and

Fellow\Lecturer

RHUL and
RAL

Outline

Introduction

- Research Interests
- Important Experiments

Dark Matter - explaining PAMELA and ATIC

- Some models to explain data
- Freeze out
- Sommerfeld effect

Summary

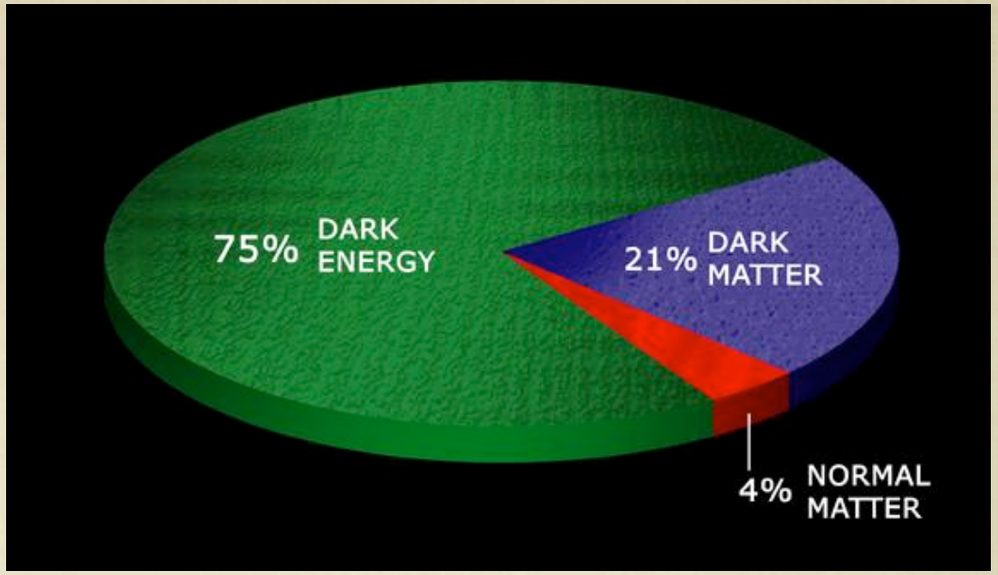
Research Interests

- BSM model building
- Supersymmetry
- Higgs Physics
- Neutrino Physics
- Flavour Physics
- Extra Dimensions
- Early Universe Cosmology
  - Baryogenesis/Leptogenesis
  - BBN
  - Dark Matter

Dark Matter

Dark matter

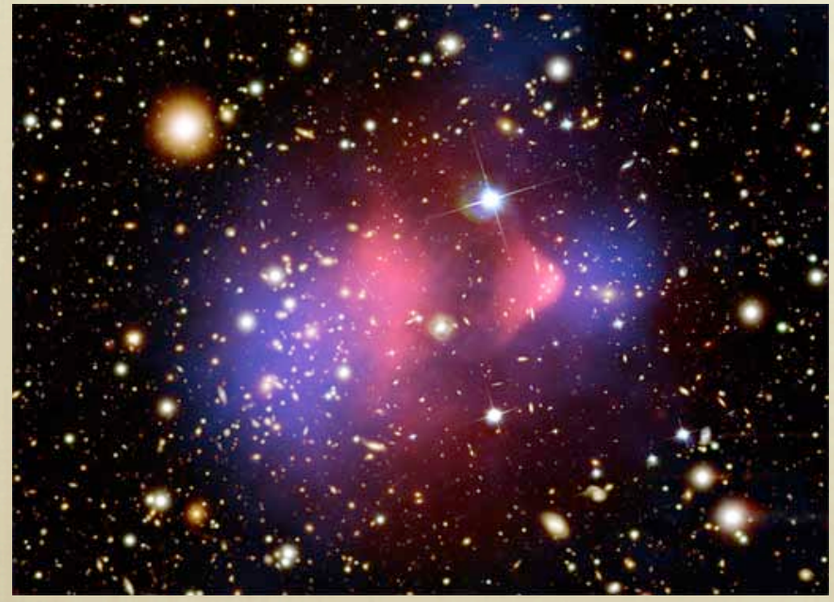
- At the LHC
- Astrophysics Experiments



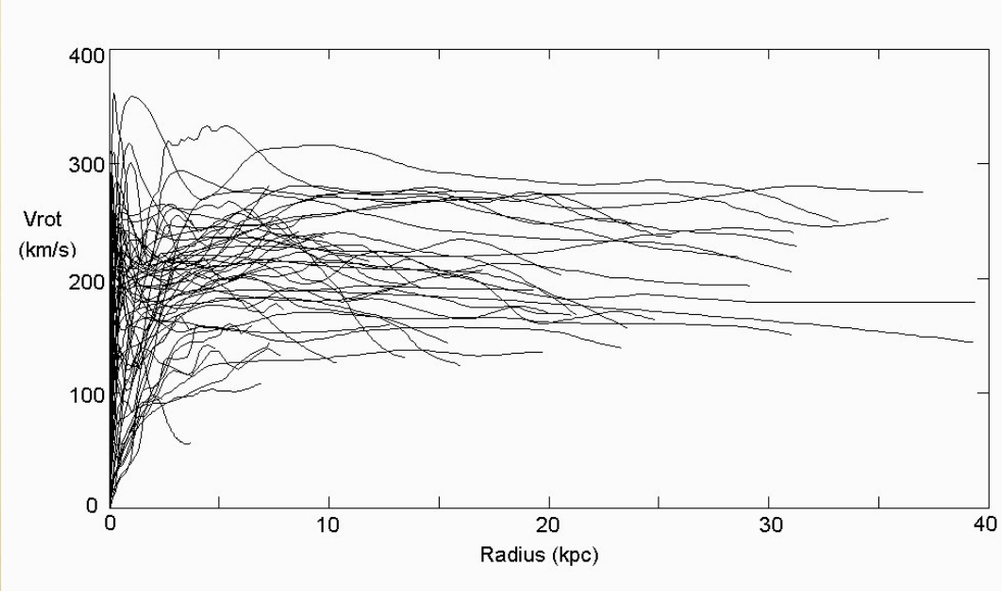
Evidence for Dark matter:

- Cosmological Scales: CMB power spectrum...WMAP $\Rightarrow \Omega h^2_{dm} = 0.1143 \pm 0.0034$

- Galaxy Cluster Scales: Bullet cluster, other cluster dynamics



- Galactic Scales: Rotation Curves, expect velocity of stars v(r) ∝ 1/√r but measure flat rotation curves



Important Experiments

Current Data:

- PAMELA $(e^{\pm}, p^{\pm})$
- ATIC $(e^{\pm}, p^{\pm})$
- Hess (γ)
- + many more

} Indirect Detection

- CDMS
- Zeplin
- DAMA
- + many more

} Direct Detection

Future Data:

- FERMI/GLAST (γ)
- Icecube (ν)
- LHC?...

Galactic Cosmic Rays (GCRs)

GCRs $\Rightarrow$ high-energy particles flowing into our solar system from far away in the Galaxy.

- Composition:

protons	$\sim 90\%$
helium	$\sim 9\%$
electrons	$\sim 1\%$
+ other heavier nuclei	

- Origins:
  - ✳ Probably accelerated in the blast waves of supernova remnants (SNRs)
  - ✳ Particles/Nuclei bouncing back and forth in magnetic field of the remnants
  - ✳ Some gain enough energy to escape into Galaxy and become GCRs

More GCRs

- Some GCRs observed with energies above max possible energies produced by SNRs

Observed range $1 - 1,000,000\ GeV/n$

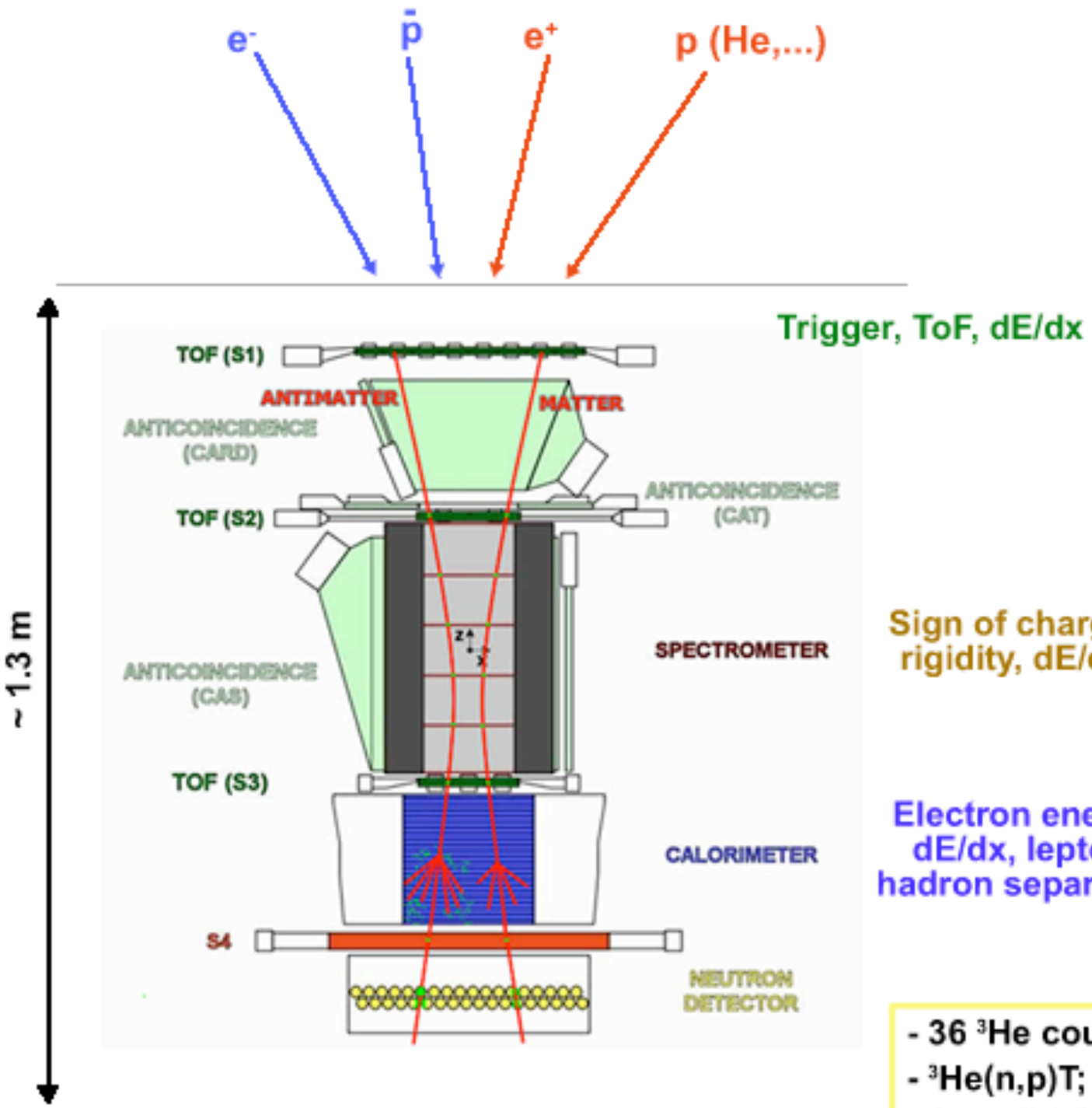
compared to $E_{max}^{SNR} \sim 10,000\ GeV/n$

- Origins?
  - Sources outside the Galaxy
  - Quasars/Pulsars
  - gamma ray bursts
  - Exotic new physics: E.G. Dark Matter...

- Some cosmic rays are observed above expected rates...

PAMELA

Payload for **A**ntimatter **M**atter **E**xploration and **L**ight nuclei **A**strophysics



Trigger, ToF, dE/dx

- S1, S2, S3; double layers, x-y
- plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

Sign of charge, rigidity, dE/dx

- Permanent magnet, 0.43 T
- 21.5 cm^2 sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MDR ~800 GV (6 plane) ~500 GV (5 plane)

Electron energy, dE/dx, lepton-hadron separation

- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm^2 sr

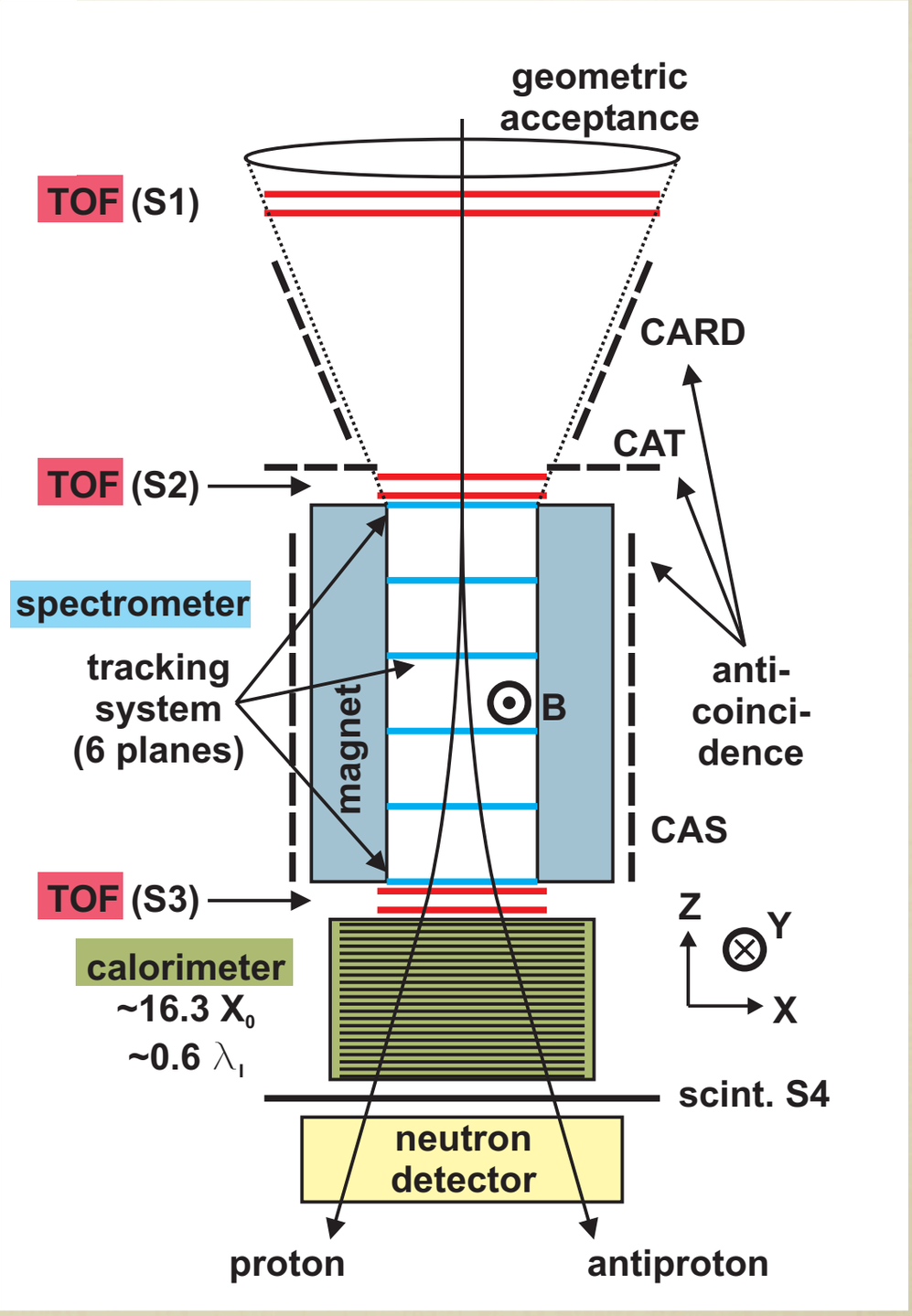
- 36 ^{3}He counters
- ^{3}He(n,p)T; E_p = 780 keV
- 1 cm thick poly + Cd moderator
- 200 μs collection

~470 Kg / ~360 W

PAMELA

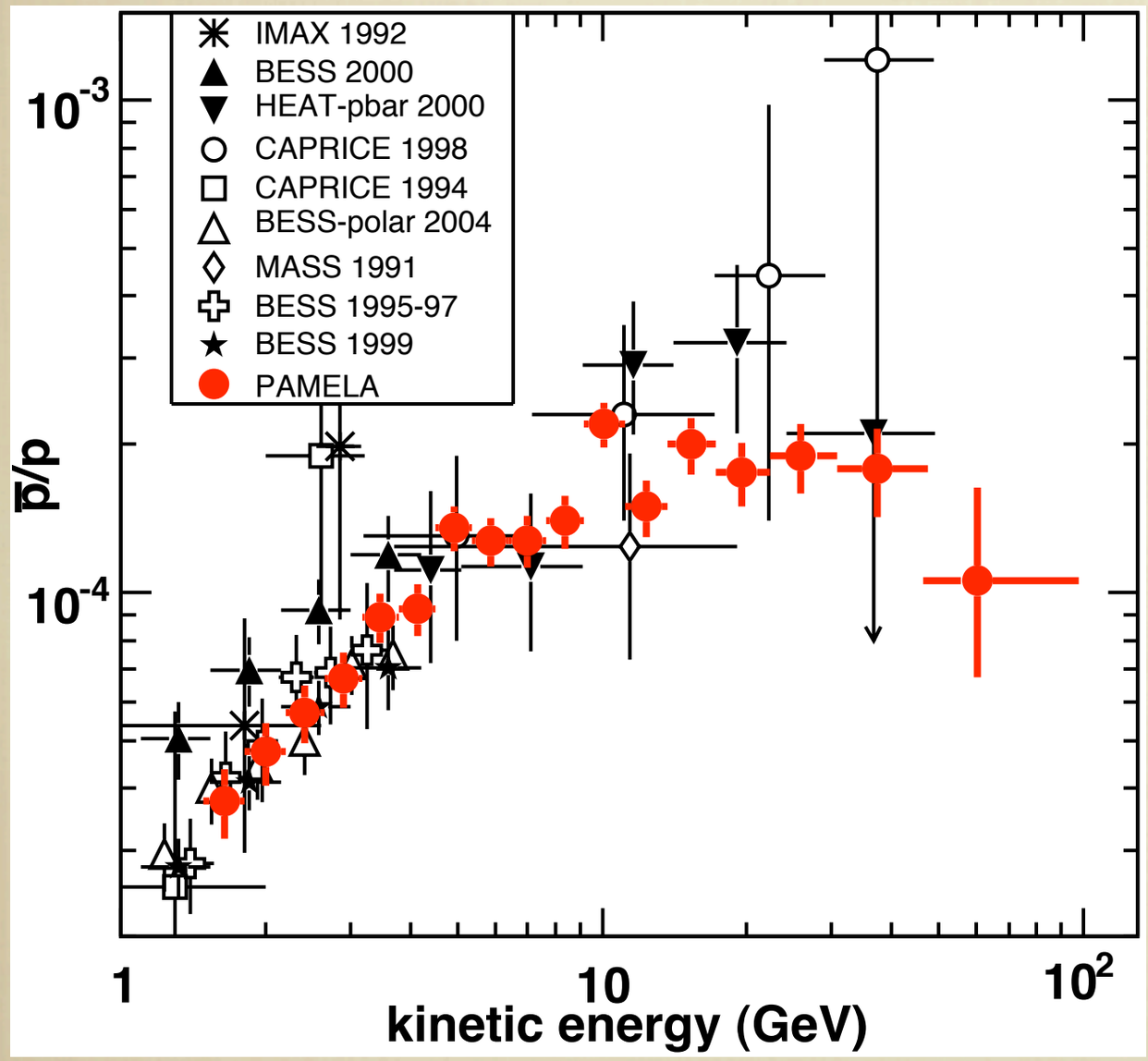
Payload for Antimatter Matter Exploration and Light nuclei Astrophysics

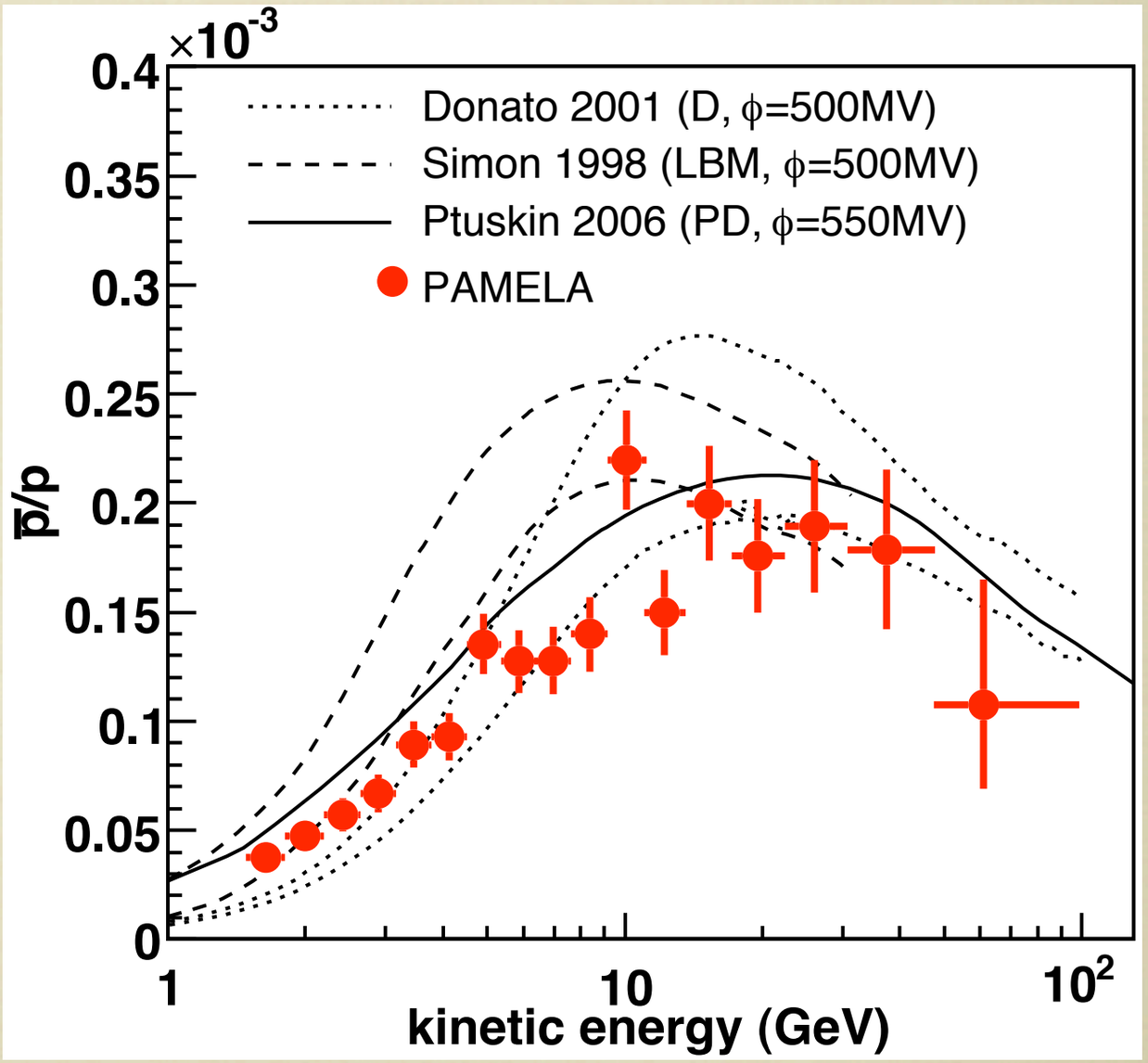
- Satellite experiment launched in 2006
- Primary goal: measure antimatter component of cosmic rays.
- Able to identify positively and negatively charged particles
- Measure spectra of antiprotons and positrons



PAMELA Results: Anti-Proton fraction

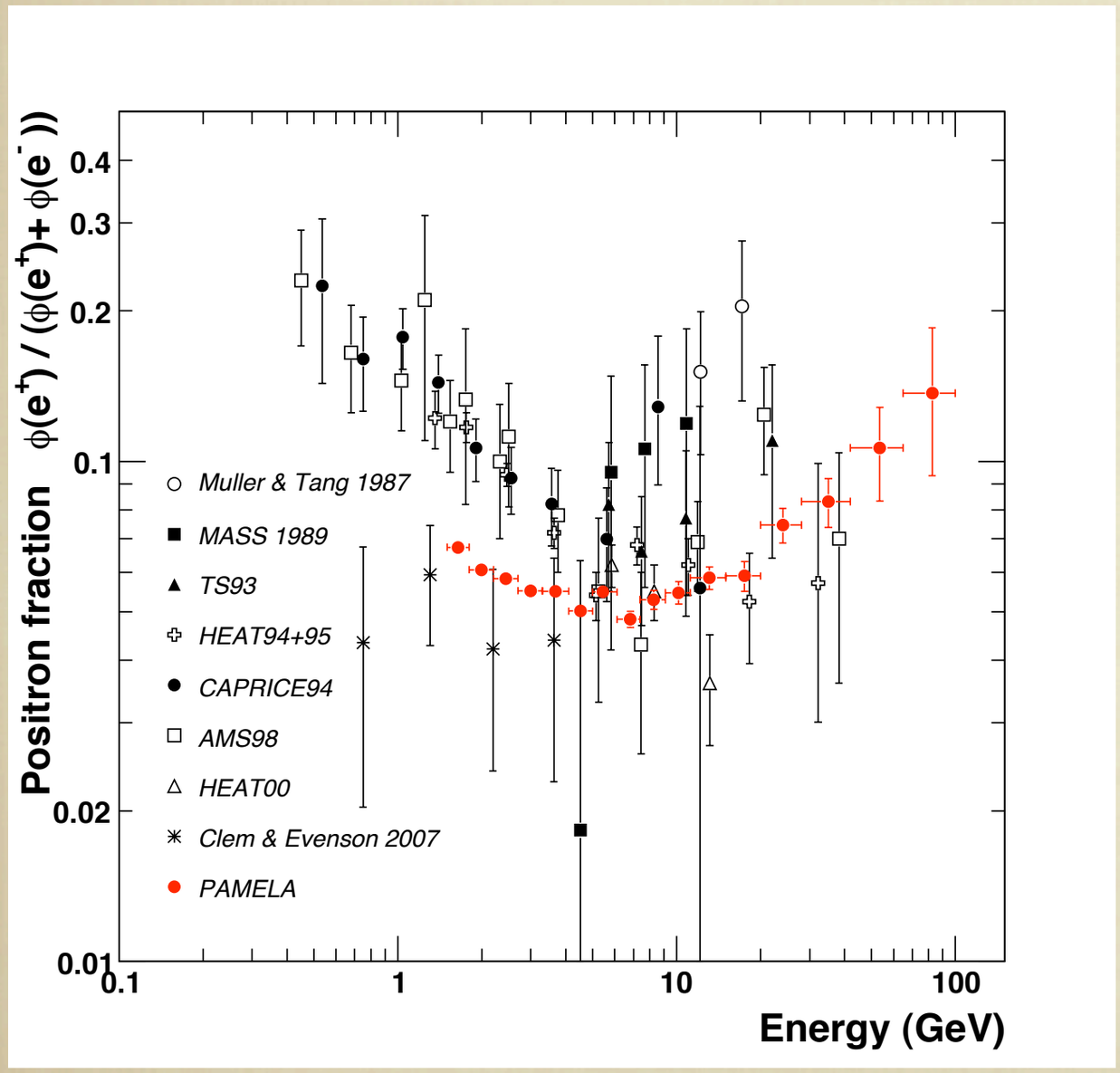
PAMELA Collaboration (O. Adriani *et al.*), **Phys.Rev.Lett.102:051101,2009.**

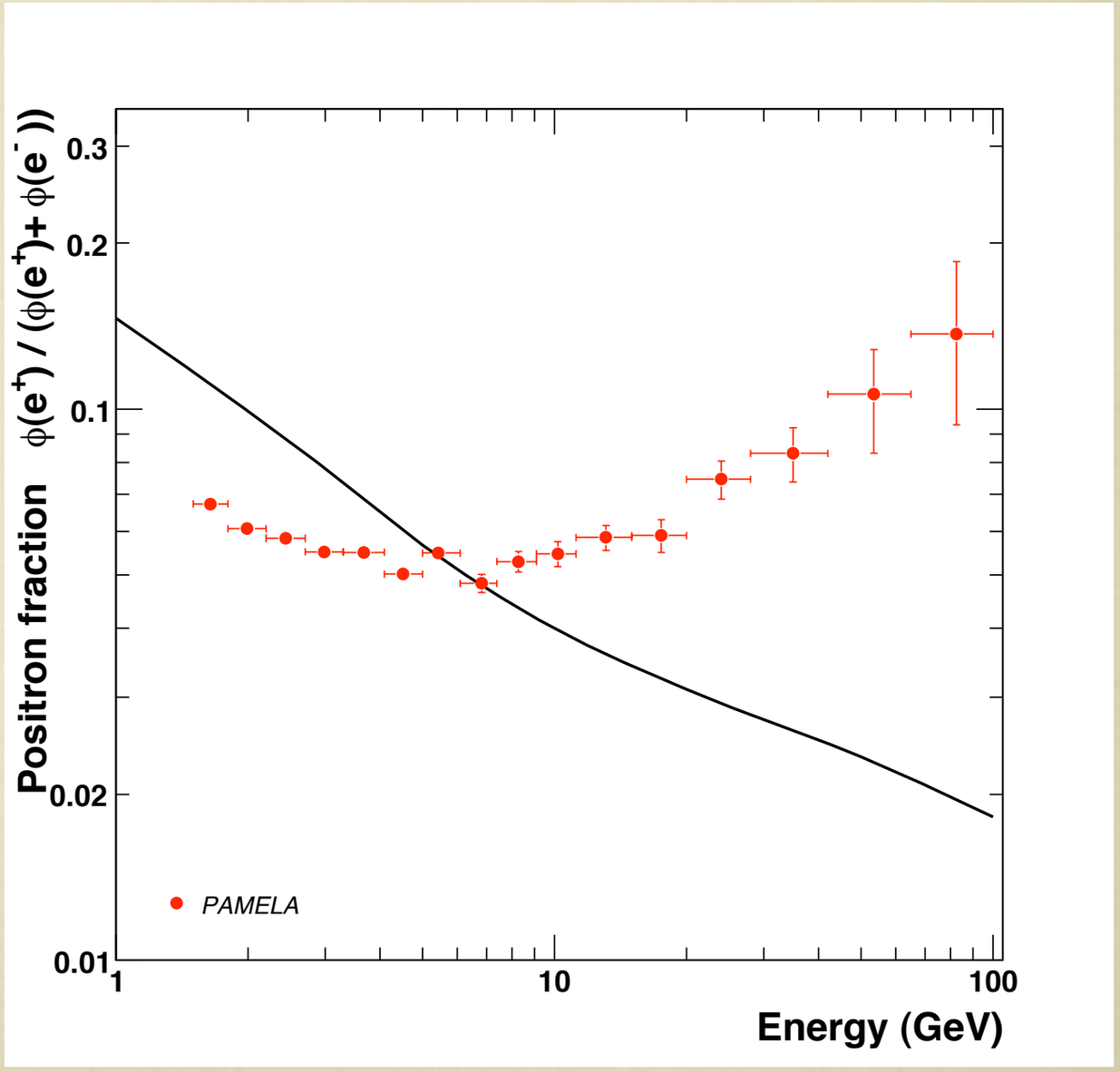




PAMELA Results: Positron fraction

PAMELA Collaboration (O. Adriani *et al.*), **arXiv:0810.4995** [astro-ph]

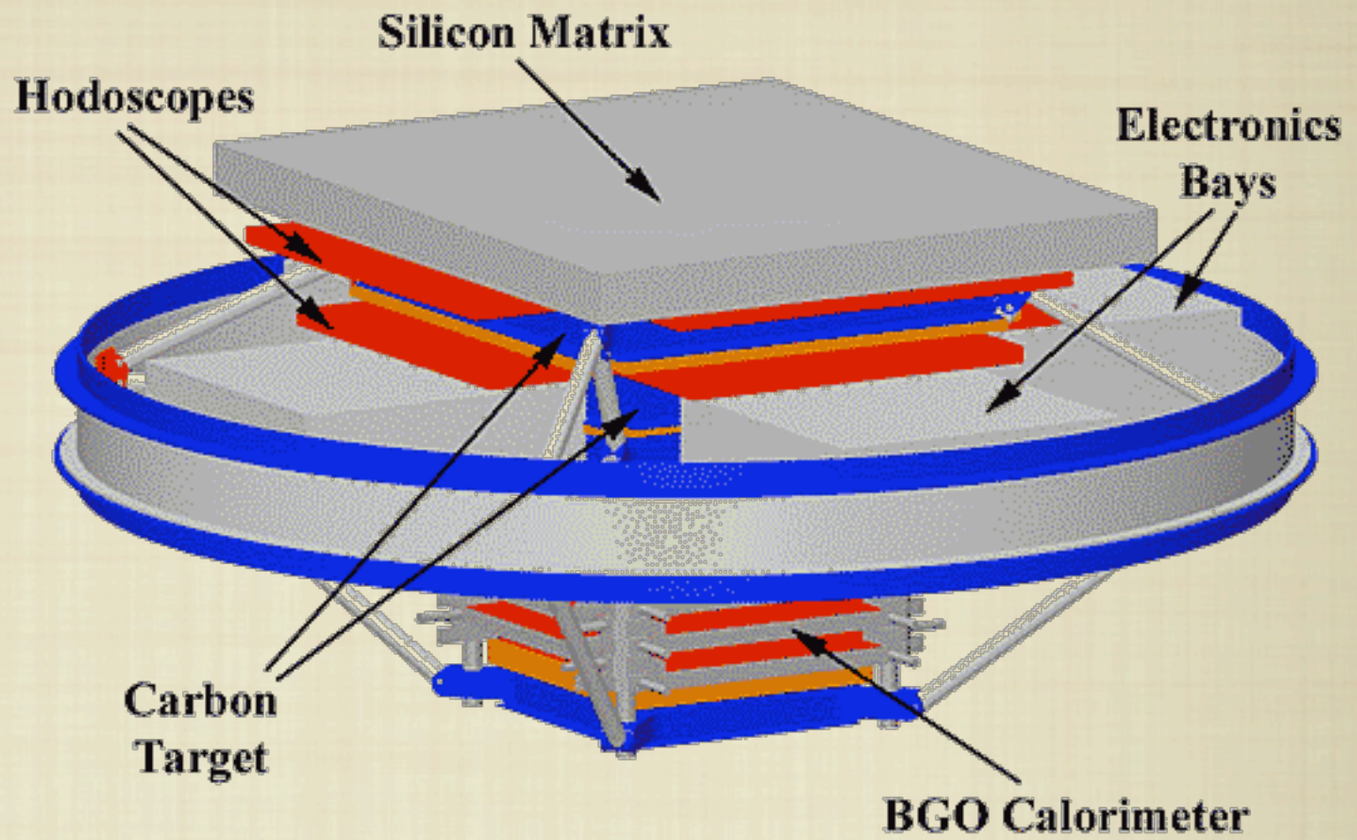




ATIC

Advanced Thin Ionization Calorimeter

- Balloon experiment collecting data in 2000, 2003 and 2007



- Cannot distinguish between e^- and e^+

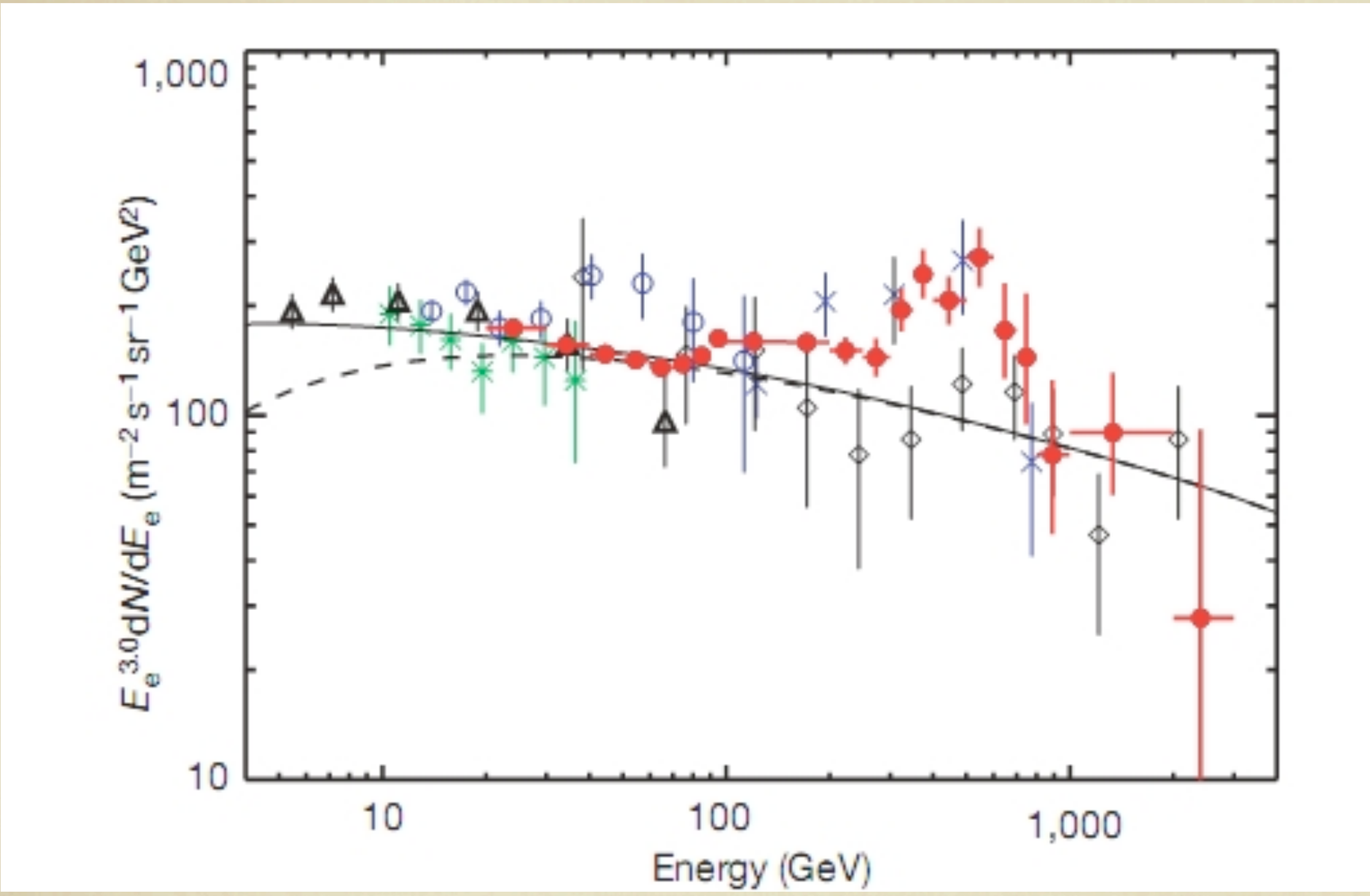
- Measures total electronic flux $(e^- + e^+)$ in energy range 20-2400 GeV

- Also detects protons and heavier nuclei

Striking Results...

ATIC results

ATIC Collaboration (J. Chang *et al.*), **Nature 456:362-365,2008.**



AMS (green stars)

HEAT (open black triangles)

Emulsion chambers (black open diamonds)

BETS (open blue circles)

PPB-BETS (blue crosses)

AMS and HEAT are satellite experiments

BETS and PPB-BETS are balloon experiments

Expected energy dependence of background

Excess corresponds to 70 out of 210 total

Explaining the rise...

- Nearby astrophysical objects e.g. Pulsars

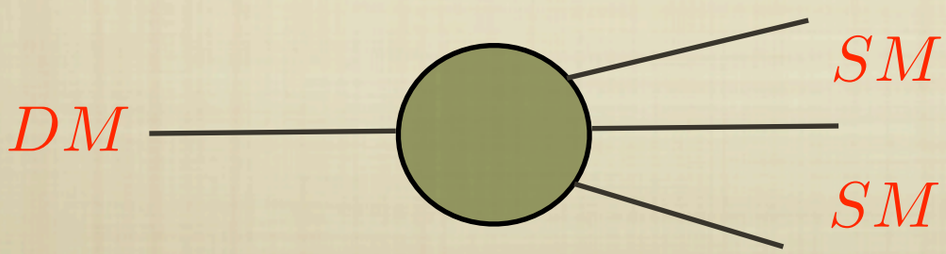
  See e.g. Büsching et al. arXiv:0804.0220
  Hooper et al. arXiv:0810.1527
  Profumo arXiv:0812.4457

  Seems possible to explain PAMELA and ATIC with pulsars

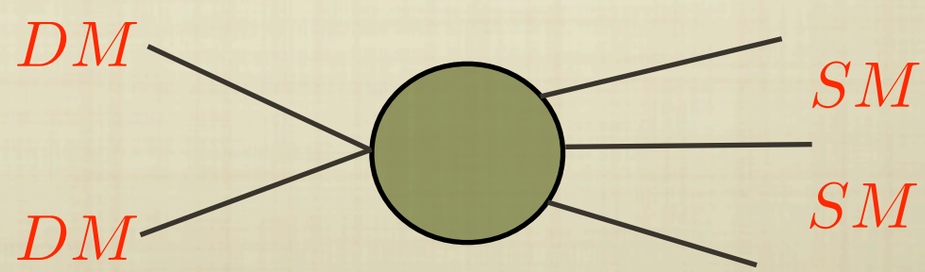
- Dark Matter

  Many refs for dark matter, see e.g. Ref list in Profumo arXiv:0812.4457

  ✳ Decays $\tau \sim 10^{26} s$



  ✳ Annihilations



Decaying dark matter

Lifetime $\Rightarrow \quad \tau \sim 10^{26} s$

Decays have restricted branching fractions:

$$B_{HAD} < 0.1$$

- Candidates:
  - Gravitino
  - "Hidden sector" particle
  - Composite particles
  - Maybe others...

Several ideas along these lines in literature

Annihilating dark matter

1) Annihilations rates must be large to account for large PAMELA and ATIC signals need boosts

- A problem for standard thermal dark matter

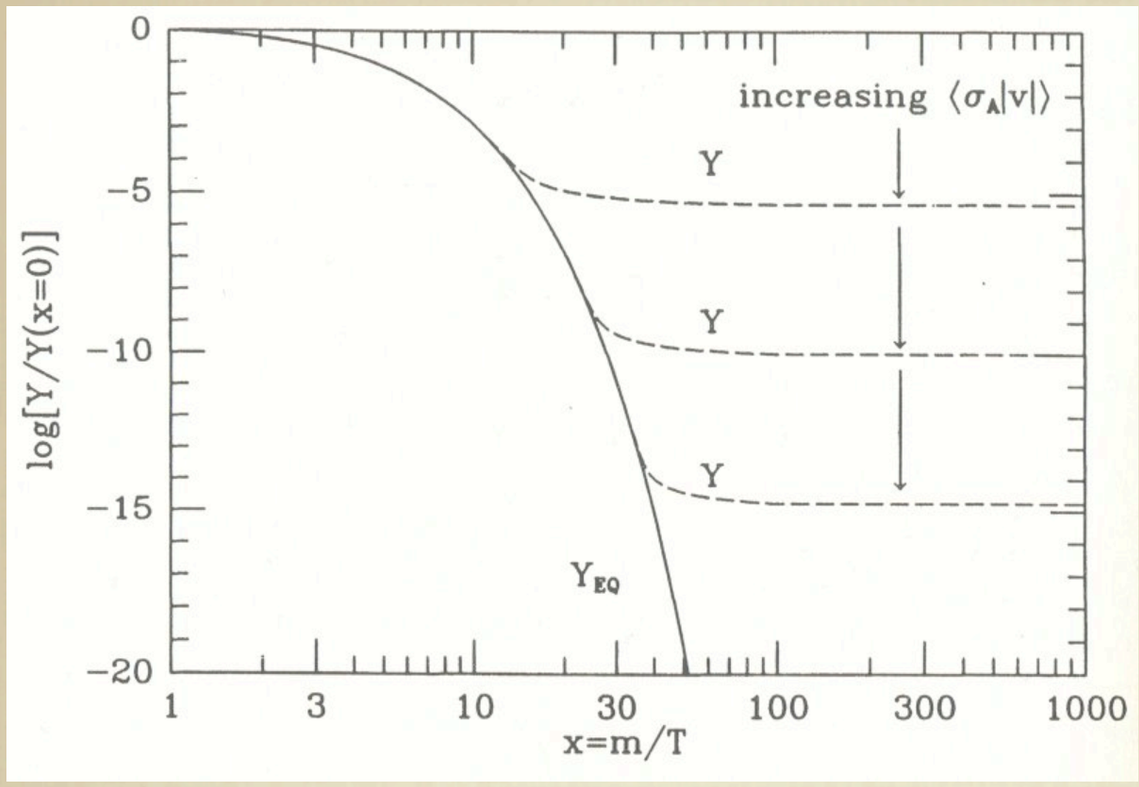
2) Annihilations must not produce too many hadrons

- Annihilation products usually include both hadrons and lepton

3) Annihilations must not produce too many photons

- Strong limits exist on photon signals
- Photons produced at wide range of frequencies for charged decay products

1) Annihilations rates must be large- problem for standard thermal dark matter



Kolb & Turner, `90

Particle in thermal eq. present abundance:

$$n_{eq} \sim (m/T)^{3/2} e^{-m/T}$$

However, if species freezes out i.e. $\Gamma < H$

at temp T such that $m/T \sim 25$

$\Rightarrow$ Can have significant relic abundance today

Using Boltzmann equations we get

$$\Omega_{dm} h^2 \sim \frac{\mathcal{O}(10^{-27} - 10^{-28})}{\langle \sigma v \rangle} GeV^{-2}$$

$$\Omega_{dm}h^2 \sim \frac{\mathcal{O}(10^{-27} - 10^{-28})}{\langle \sigma v \rangle} GeV^{-2}$$

But we know that $\Omega_{dm}h^2 = 0.1143 \pm 0.0034$

$$\Rightarrow \langle \sigma v \rangle = (10^{-26} - 10^{-27}) GeV^{-2}$$

This is weak scale interaction with weak scale mass particle

$\Rightarrow$ WIMP

This fixes $\langle \sigma v \rangle$

$\Rightarrow$ sets the size of annihilations of DM particles as a function of DM velocity

!! A way out !! Change how $\langle \sigma v \rangle$ depends on velocity

The Sommerfeld Effect

Normally $\sigma v = a + bv^2$

- Heavy DM moving at small (relative) velocity
- Exchange of scalar (or vector) state

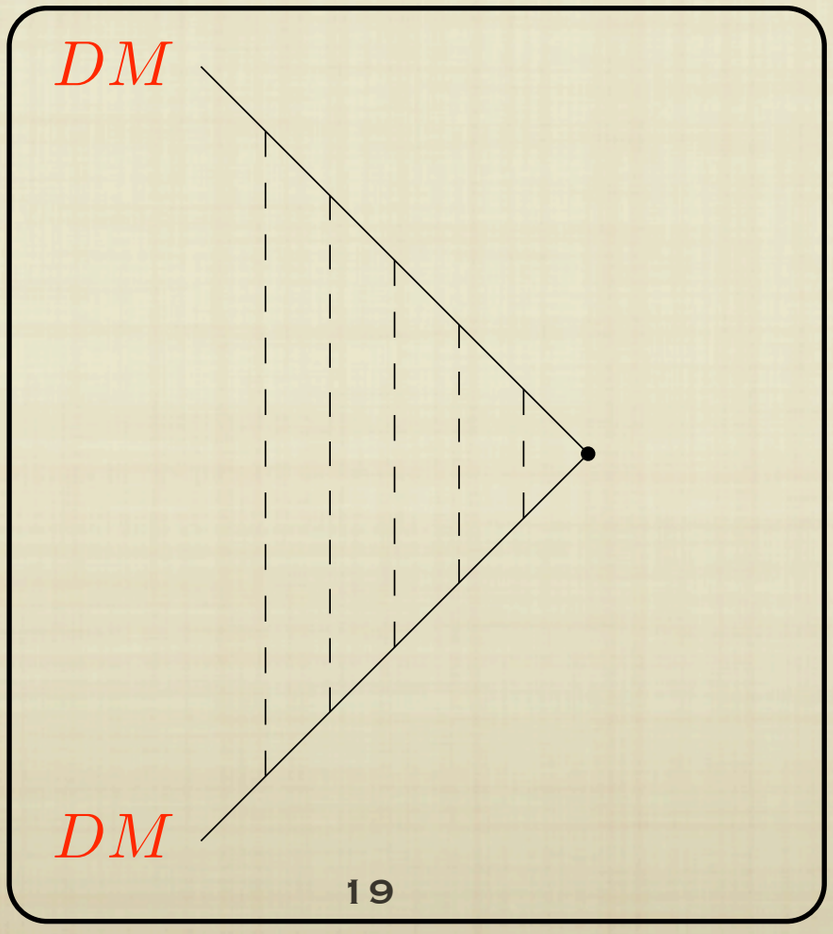
enhancement in annihilation cross section $\Rightarrow \sigma v \propto \frac{1}{v_r}$

(Sommerfeld; Hisano et al, Strumia et al...)

March-Russell, West, Cumberbatch, Hooper.

- Corresponds to summation of diagrams

$\Rightarrow$



Only significant for s-wave

(AM barrier)

The Sommerfeld Effect

- Calculation formed in terms on non-rel two body QM problem with a potential
- Equivalent to distorted Born-wave approximation common in nuclear physics.
- Including the effect (to a good approximation)

$$\sigma = R\sigma_{tree}^{l=0}$$

- Full calculation of R can be involved
- For a Yukawa potential R cannot be solved analytically
- Can be enhancement or suppression for vector exchange

Calculating R

- Introduce the following term $\frac{\lambda}{2} n \psi_{dm} \psi_{dm}$

- Scalar n states can be the "rungs on the ladder"

- The Schrödinger equation for two DM particle state $\psi \sim \psi_{dm}\psi_{dm}$

$$-\frac{1}{m_{dm}}\frac{d^2\psi}{dr^2} + V\psi = K\psi$$

$$V = -\frac{\lambda^2}{8\pi r} e^{-m_n} \qquad K = m_{dm} v^2$$

- Enhancement factor

$$R = |\psi(0)/\psi(\infty)|^2$$

- Outgoing B.C $\psi'(\infty)/\psi(\infty) = i m_{dm} v$

Coulomb limit

- Analytic form for R in limit $\epsilon \equiv m_n/m_{dm} = 0$

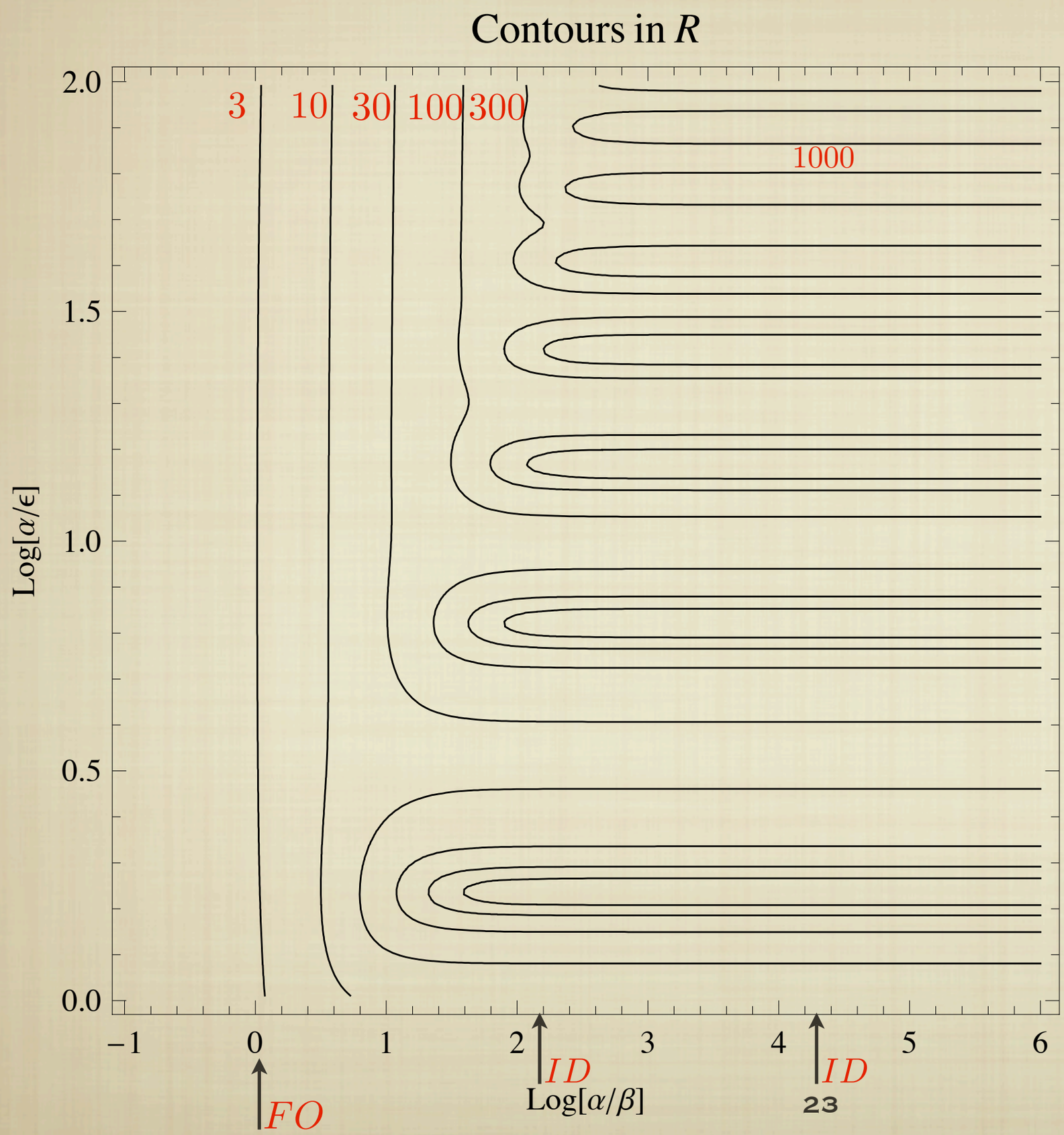
$$R = \frac{y}{1 - e^{-y}} \qquad y = \lambda^2/4v$$

- Small v limit

$$R \approx \frac{\lambda^2}{4v}$$

What about $\epsilon \neq 0$?

Enhancement for $\epsilon \neq 0$



$$\epsilon \equiv m_n/m_{dm}$$

$$\alpha = \lambda^2/8\pi$$

Need

$$\alpha/\epsilon > 1$$

$$\alpha/\beta > 1$$

Freeze out

$$\beta \sim 0.2$$

$$\Rightarrow \lambda \sim 2$$

$$\Rightarrow \uparrow_{FO}$$

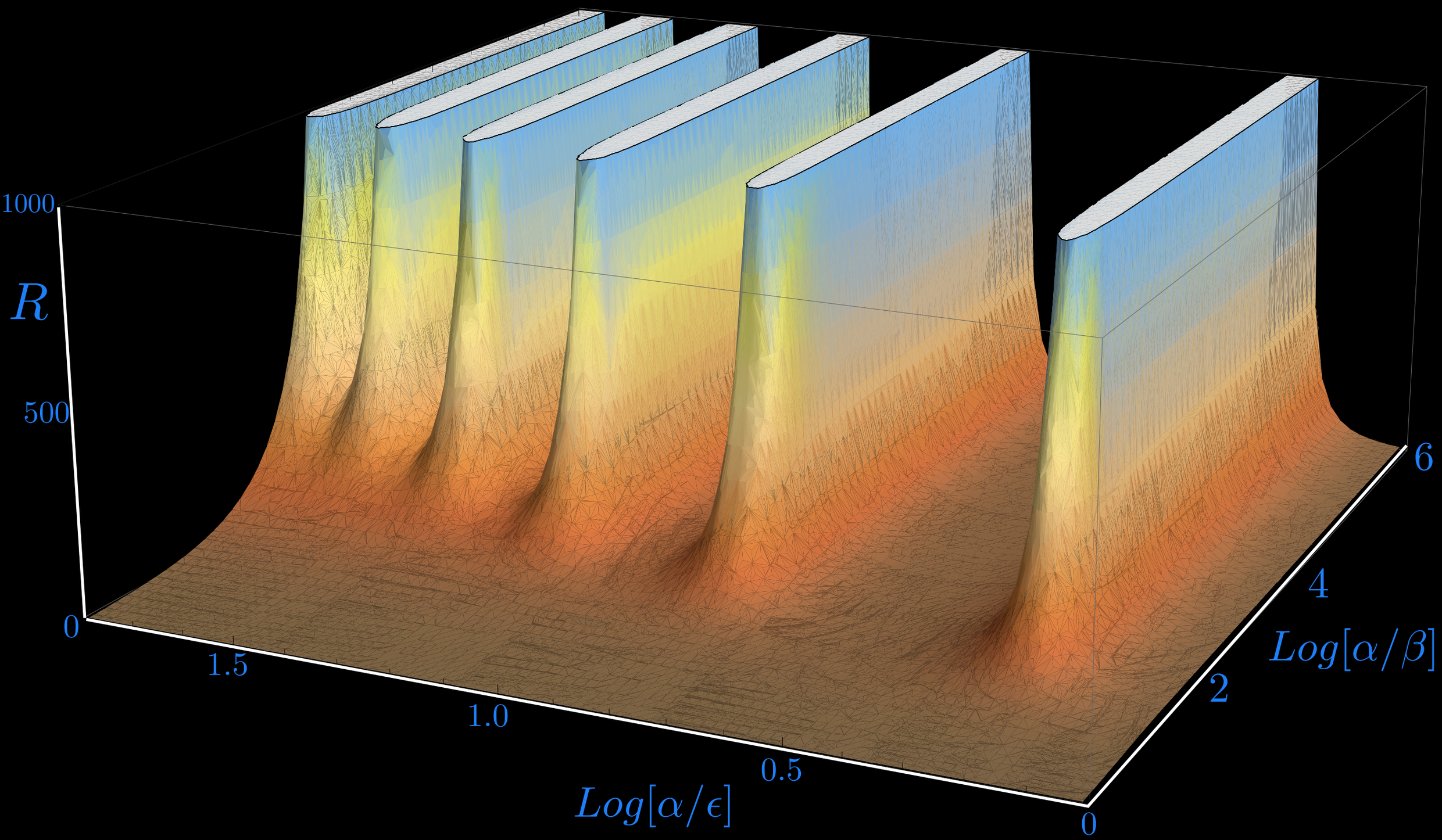
Indirect detection

$$\beta \sim 10^{-3} - 10^{-5}$$

$$\Rightarrow \uparrow_{ID}$$

3D Version

March-Russell, West.



1) Annihilations rates must be large - Alternatives

- Could consider non-thermal dark matter
  - Late decaying particles
  - Another interesting idea later
- Over densities - No. annihilation $\propto \rho_{dm}^2$
  - Regions of high density
  - Near Black Holes?
  - Naturally occurring clumps?

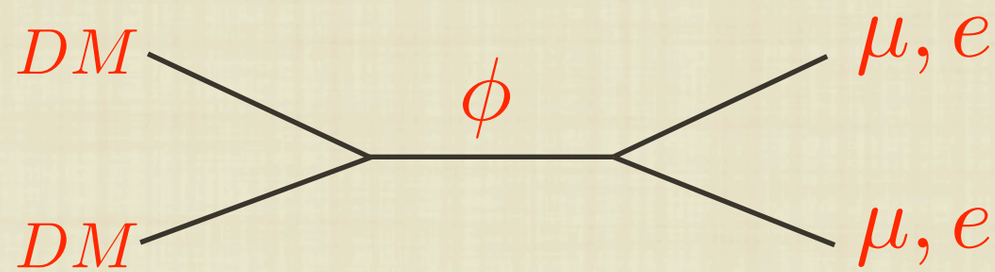
2) Annihilations must not produce too many hadrons

- Leptophilic models

  Fox, Poppitz, arXiv:0811.0399

  - Need to introduce extra quantum numbers
  - dark matter only talks to leptons due to symmetries

- Kinematic tricks and extra symmetries



(Arkani-Hamed et al...)

- Particle ϕ can generate Sommerfeld enhancement
- Can introduce two dark matter states and have inelastic scattering

$\Rightarrow$ possible to reconcile DAMA with other direct detection experiments

3) Annihilations must not produce too many photons

- All annihilations with charged states can produce photons
  - Boosting annihilation rates into $e^{\pm}$ means we produce more photons
  - Measurements of Cosmic diffuse background radiation tightly constrain scenarios

Summry

- PAMELA and ATIC inspired a lot of model building
- Maybe explained by astrophysics
- If DM is the answer, need large boosts to annihilation cross sections
- Several ways to generate boost factors but all have restrictions and constraints
- PAMELA and ATIC data have inspired a lot of unusual and compelling new ideas - many more to come...

✷ Exciting times ahead