DARK MATTER SEARCHES FROM THE GALAXY TO THE LHC – RECENT HINTS AND COMING PROGRESS

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We know how much dark matter there is (about ¼ of mass-energy density of the universe) but not what it is.

The Standard Model ***cannot*** provide a dark matter candidate – when we find it, it will increase our understanding of ¼ of the universe, ***and*** point toward the underlying theory that extends the SM

Is it a particle whose properties we can measure in the lab, and at LHC? Very good candidates exist, such as the lightest superpartner, LSP

Suppose a candidate DM particle is found – how can we decide if it actually does give the relic density? -- Can never measure the relic density of a given candidate! Must calculate it!

Neutrinos provide about 0.5% of the relic density of DM. Complete theories typically have massive neutrinos and axions and a lightest superpartner that each can give dark matter. Too important to trust NY Times level arguments.

ARE WE BEGINNING TO SEE DARK MATTER? PERHAPS!

PAMELA satellite experiment has reported an excess of galactic positrons, qualitatively confirming earlier HEAT and AMS reports

Such an excess possible from dark matter particles – they annihilate in the galaxy – final states contain annihilation products – may see positrons, antiprotons, photons over backgrounds

There are constraints on any such interpretation

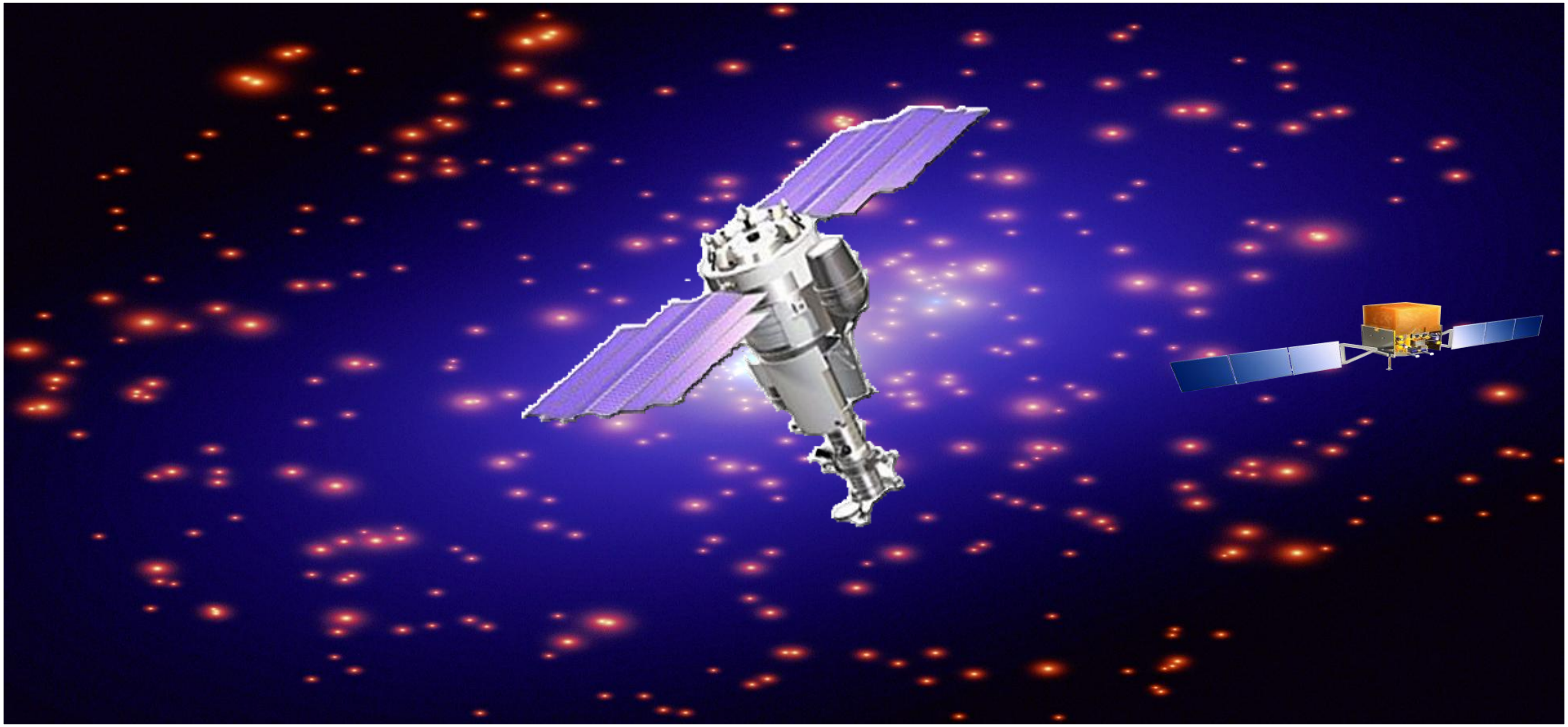
- Get sufficient positrons from legitimate particle candidate?
- Also see it in antiprotons? X
- Also see it in synchrotron radiation (WMAP) or in gammas (EGRET) X
- Also see it in “direct” detection (DM candidate scatters off nuclei in a detector)? ??
- Also see it in neutrinos from DM annihilation in the sun? X

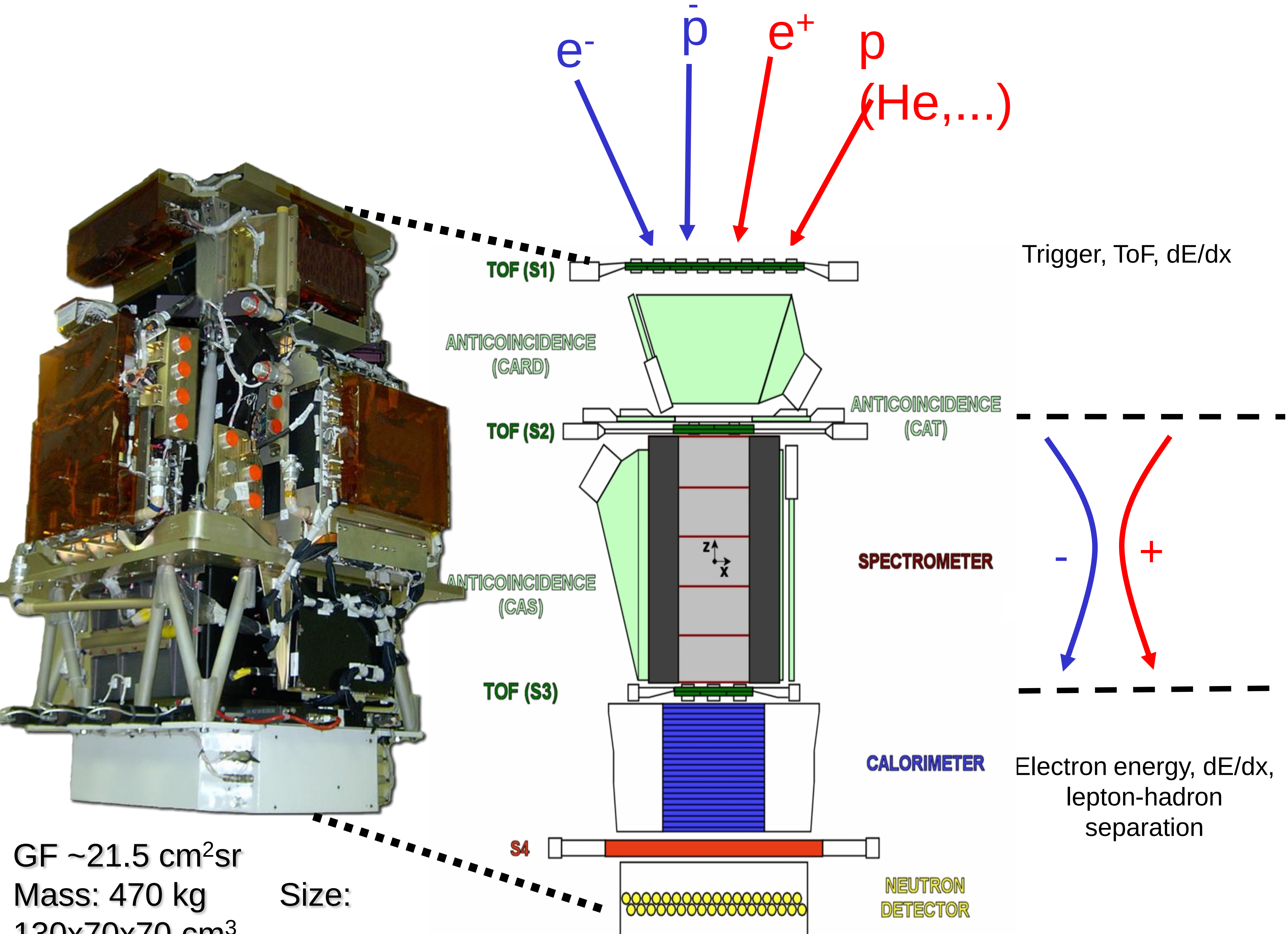
Any interpretation must be consistent with all these and more.

OUTLINE OF TALK

- Can the reported PAMELA galactic positron excess be interpreted as a signal of dark matter?
- If so, can it be related to the (controversial) reported DAMA annual modulation?
- Calculating the relic density of any DM candidate – large annihilation cross section probably requires non-thermal cosmological history
- DM and LHC

PAMELA Space Mission





GF ~21.5 cm^{2}sr

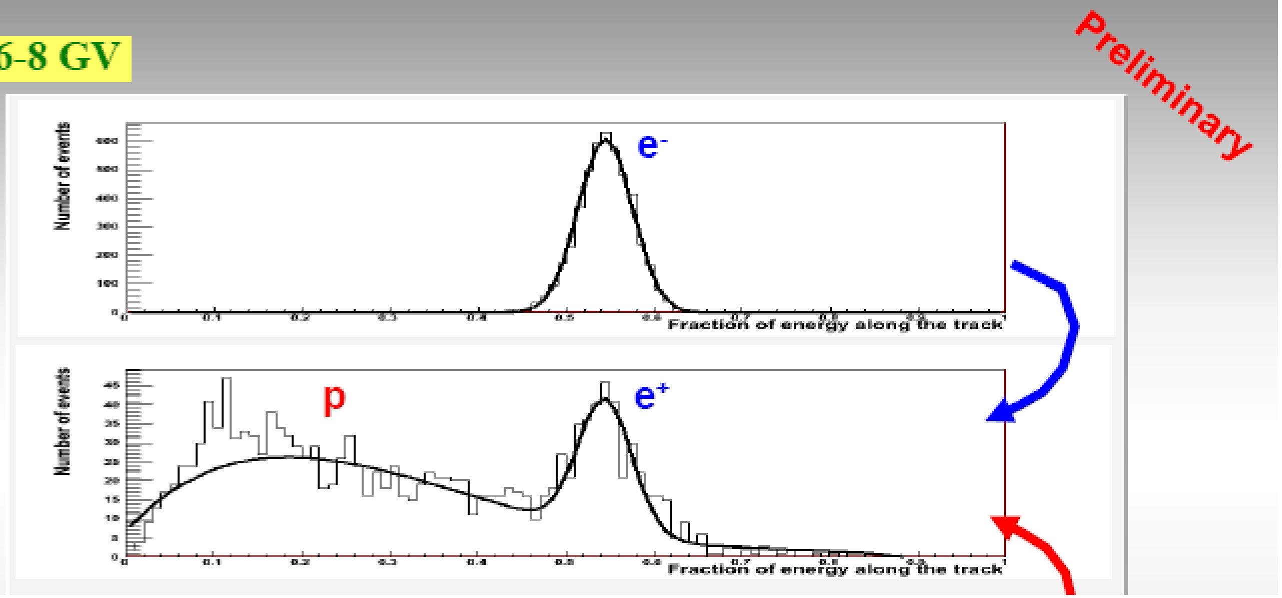
Mass: 470 kg

Size: 130x70x70 cm^3

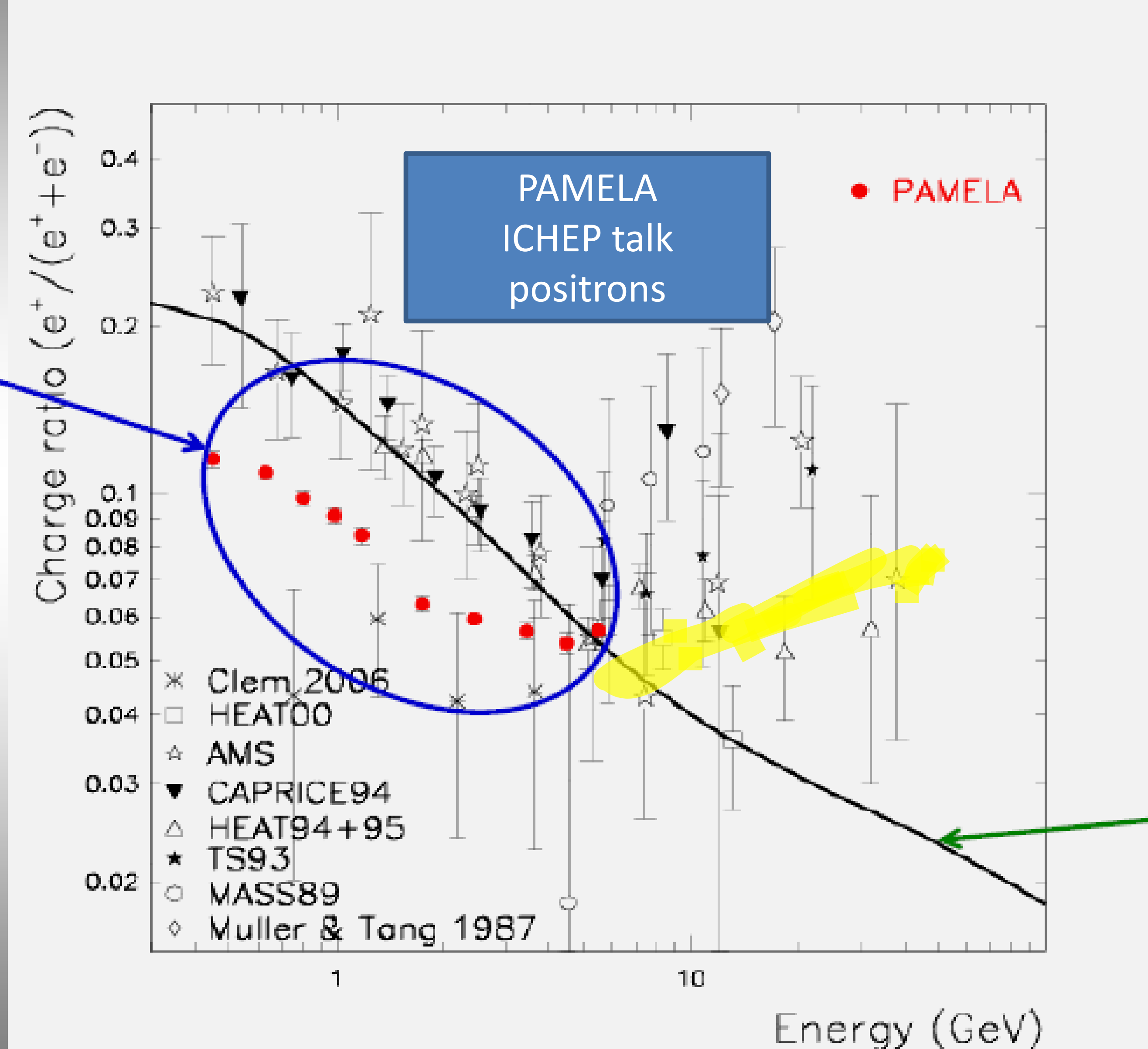
Energy range

Antiproton flux	80 MeV - 190 GeV
Positron	50 MeV – 270 GeV
Electron/positron flux	up to 2 TeV (from calorimeter)
Electron flux	up to 400 GeV
Proton flux	up to 700 GeV
Light nuclei (up to Z=6)	up to 200 GeV/n

Rigidity: 6-8 GV



Charge sign dependent solar modulation

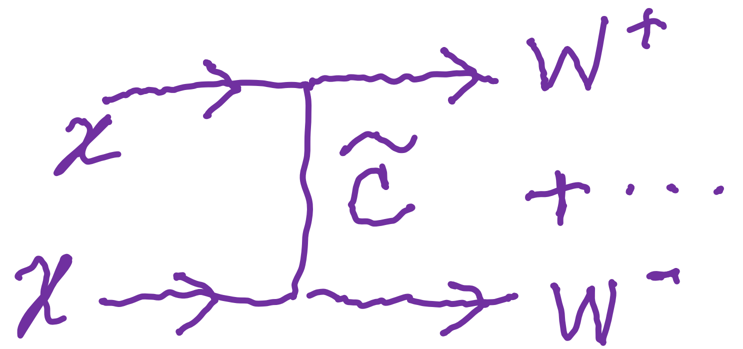


nd 2007:
20 000
sitrons total

Work in terms of LSP DM – well motivated, fits in underlying theory, call it χ

$\chi = \alpha\tilde{W} + \beta\tilde{h} + \gamma\tilde{B}$

Mainly wino LSP works well to get positrons – bino gives few positrons from annihilation



Because annihilation is to W^+W^-, any dark matter particle χ in mass range $M_W < M_\chi \lesssim 250$ GeV is likely to be a good candidate

Then W's decay to $e\nu$, $\mu\nu$, $\tau\nu$, quarks, etc

Quarks → antiprotons, π^0, radiated photons in microwave, gammas

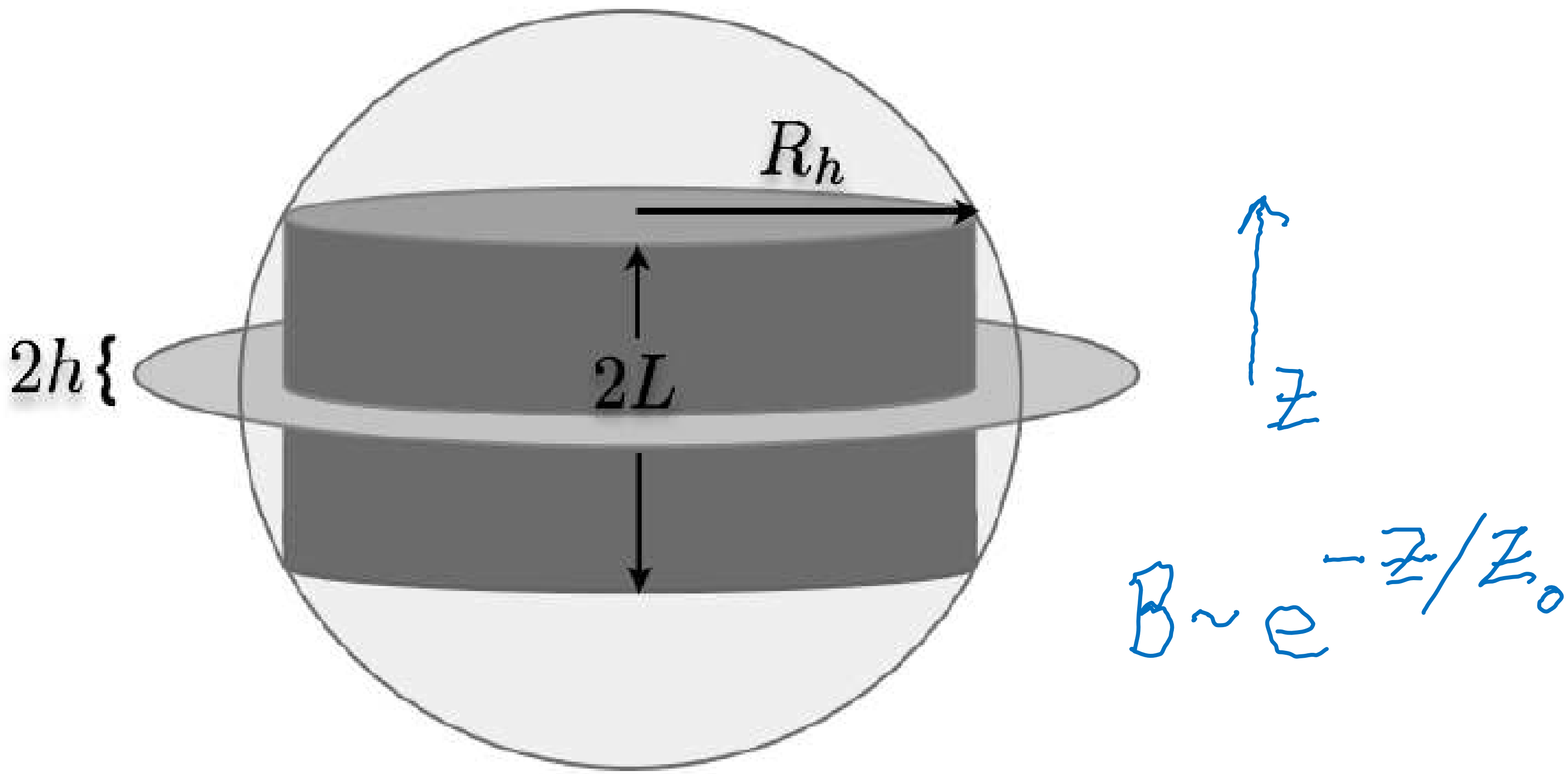


Figure 1: The diffusion zone (cylinder) is taken to have a height $2L$, with L in the range of 4-12 kpc [27], whereas the radial direction is taken as $R_h = 20$ kpc (see figure 1). Most of the interstellar gas is confined to the galactic plane at $z = 0$, which represents a slice through the cylinder and has a height of $2h = 100$ pc. Our solar system is then located in this plane at a distance of around $r_0 = 8.5$ kpc from the galactic center. All of this is enveloped by a spherically symmetric dark matter halo.

- DM annihilations occur in the galactic plane and in the DM halo
- Lifetime in galaxy long, $\sim 10^7$ years
- Some charged annihilation products escape, some are confined in the galaxy – they lose energy, diffuse
- We are about 8.5 kpc from galactic center
- Energy loss from bremsstrahlung, Coulomb scattering, inverse Compton scattering on starlight and CMB photons (e^+), synchrotron radiation (e^+)
- GALPROP (Moskalenko, Strong)
- Positrons lose energy well and those above $\sim$ 5 GeV come from region within 3-4 kpc from us
- Antiprotons do not lose energy easily, so they come from a larger region, can sample inner galaxy region
- Gammas from everywhere
- Microwave synchrotron radiation (WMAP 22GHz) – not enough? (Finkbeiner, Hooper)

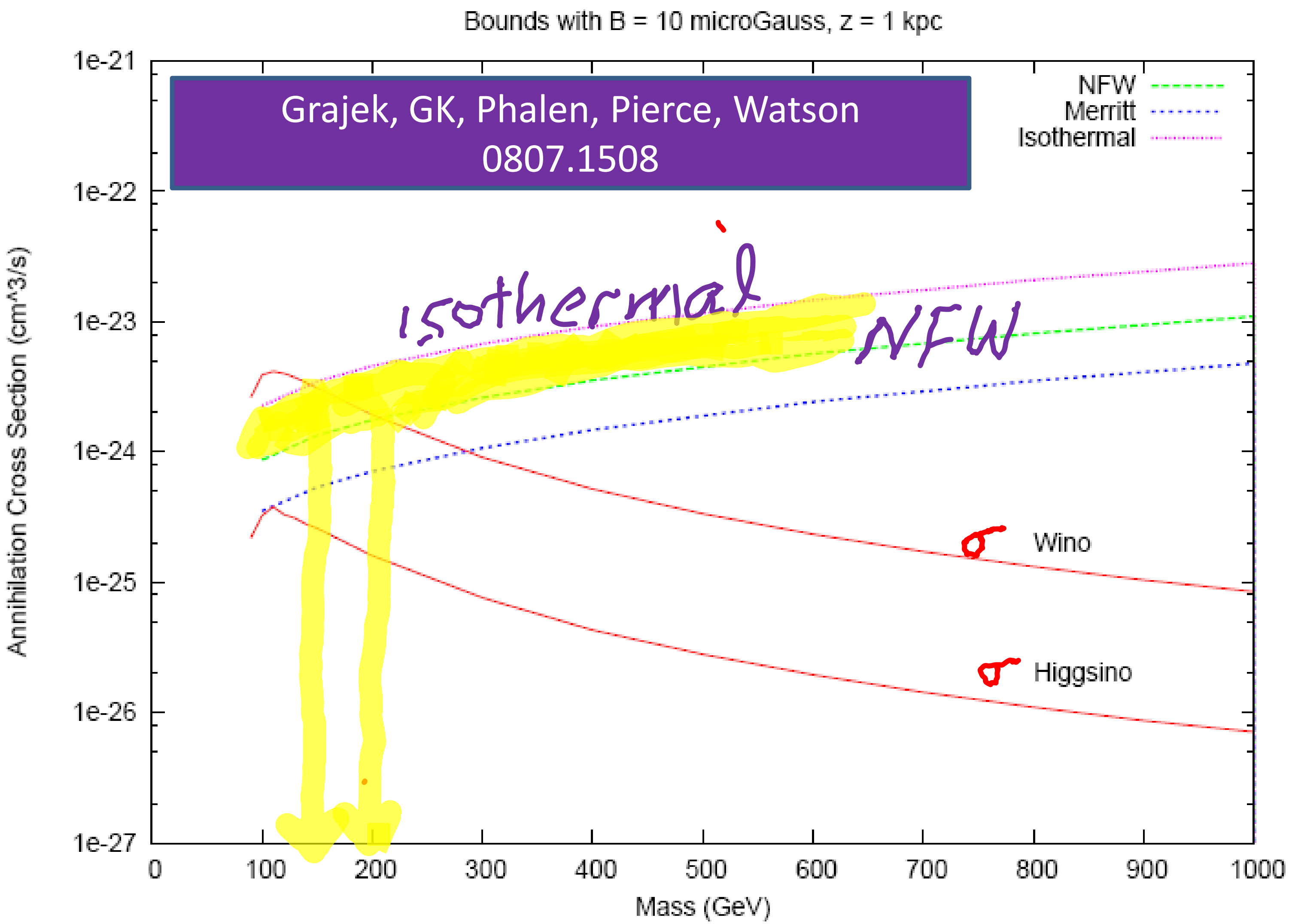
PROFILE OF DM IN GALAXY SIGNIFICANT

- N body simulations somewhat prefer ones cusped at center of galaxy (NFW)

$$\rho(r) \sim [\ ]/r$$

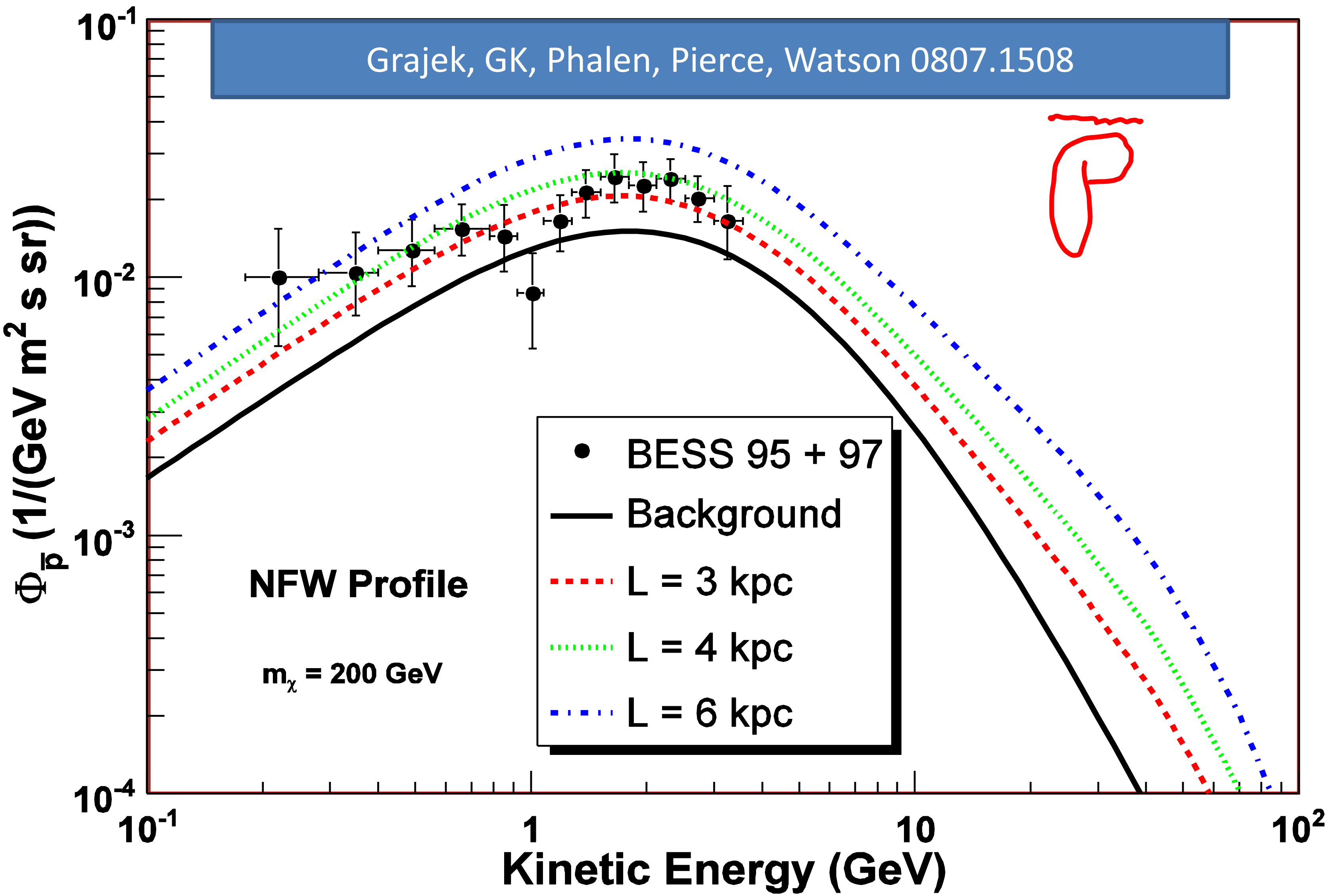
- Observations seem to favor “isothermal cored” ones, softer at center

$$\rho(r) \sim [\ ]$$

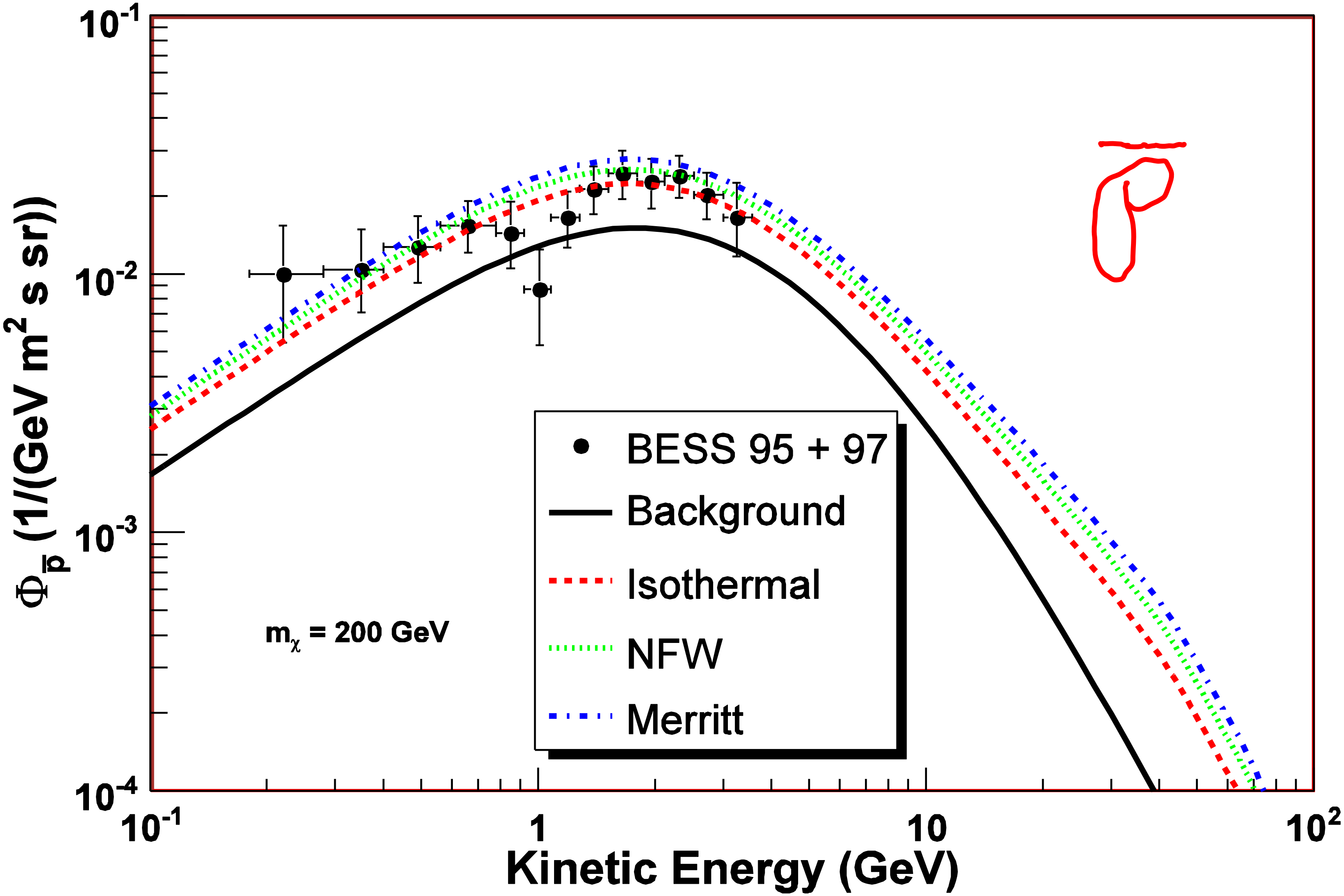


Galactic synchrotron radiation implies $M_\chi \lesssim$ 200 GeV and profile softer than NFW

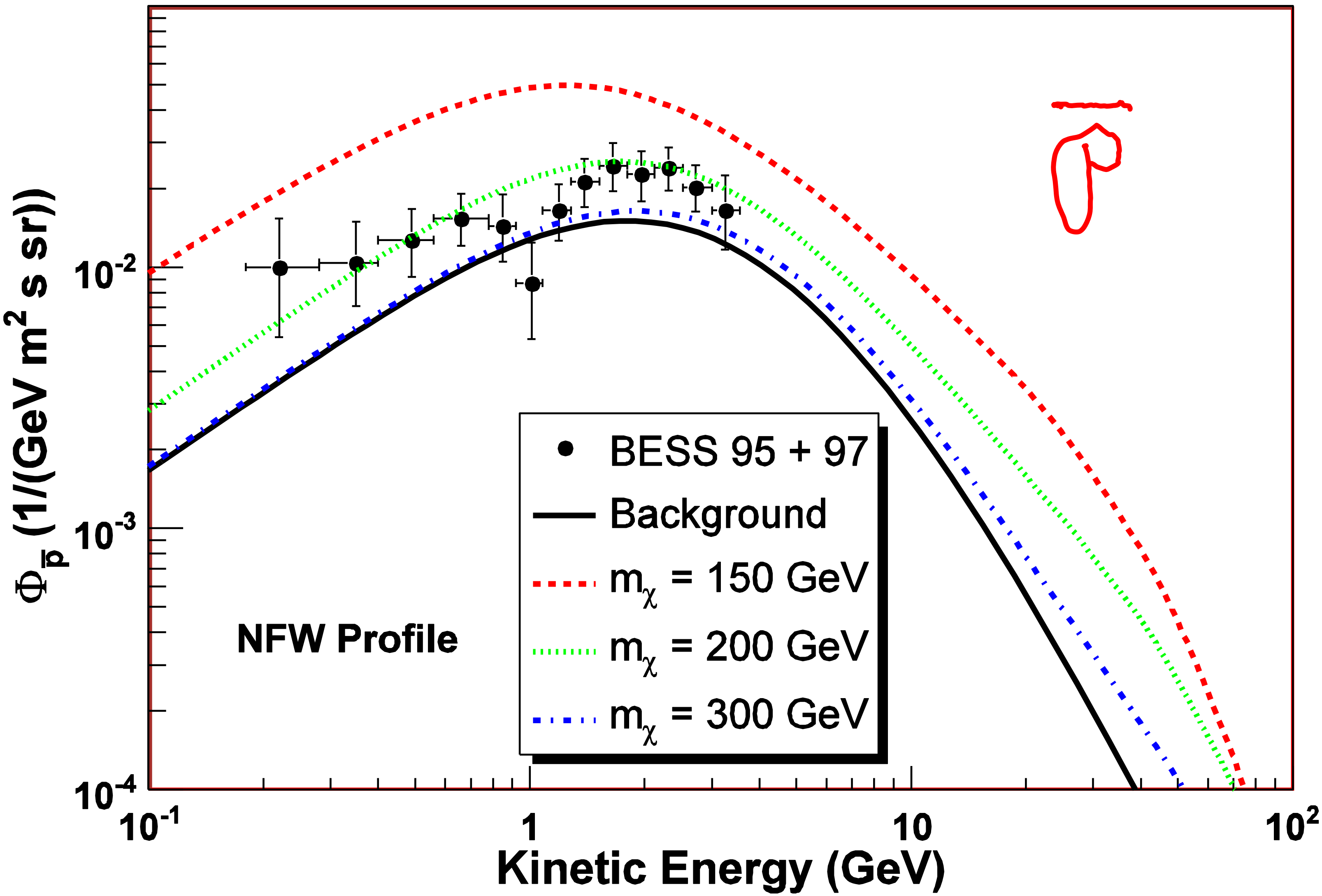
Figure 6: Bounds on the annihilation cross section into W^+W^- from synchrotron radiation. We have used the propagation parameters described in the text and only vary the magnetic field properties here.



Grajek, GK, Phalen, Pierce, Watson 0807.1508
$\Phi_{\bar{p}}$ (1/(GeV m^2 s sr))
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-1}
1
10
10^2
Kinetic Energy (GeV)
BESS 95 + 97
Background
L = 3 kpc
L = 4 kpc
L = 6 kpc
NFW Profile
m_χ = 200 GeV
$\bar{p}$

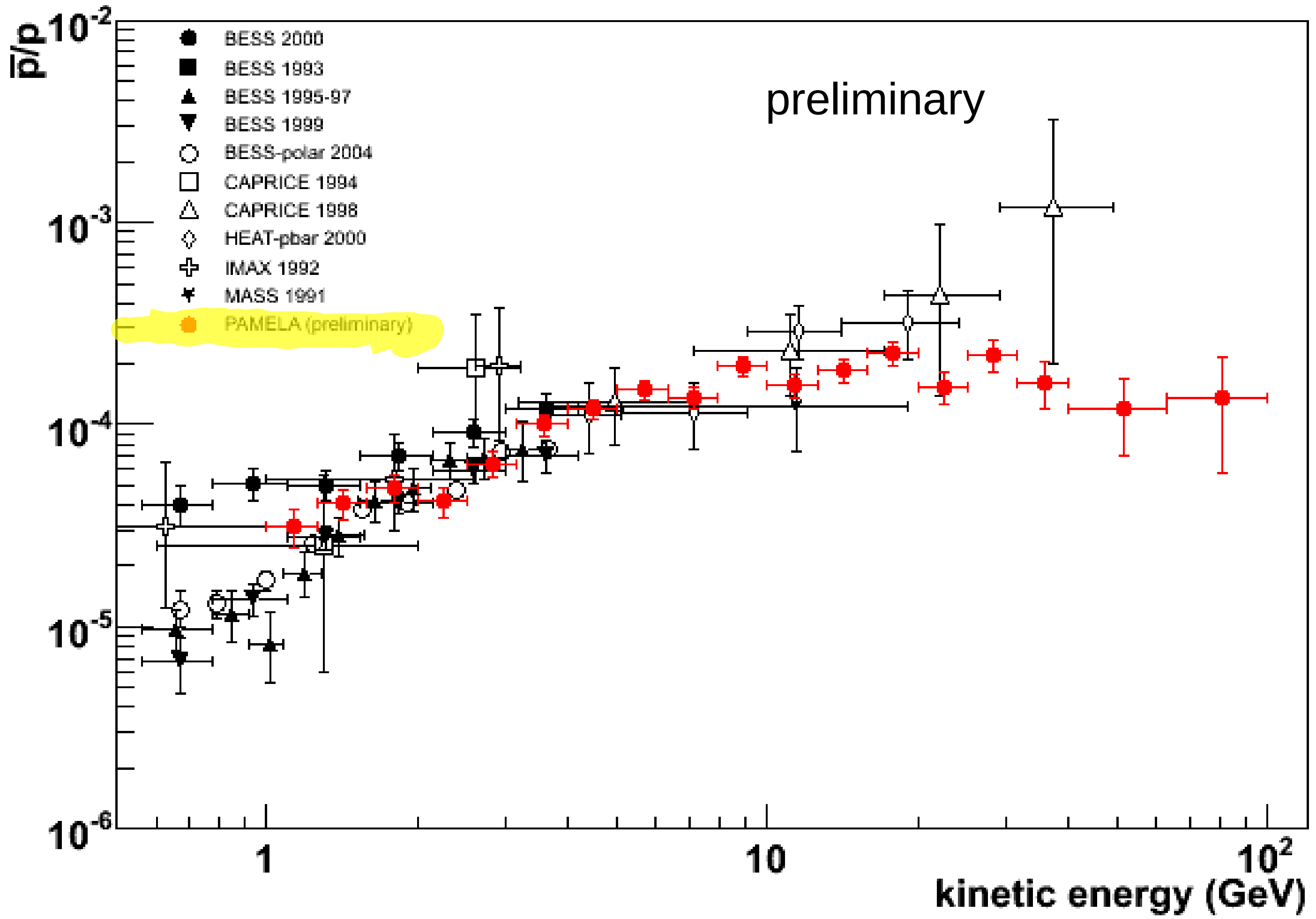


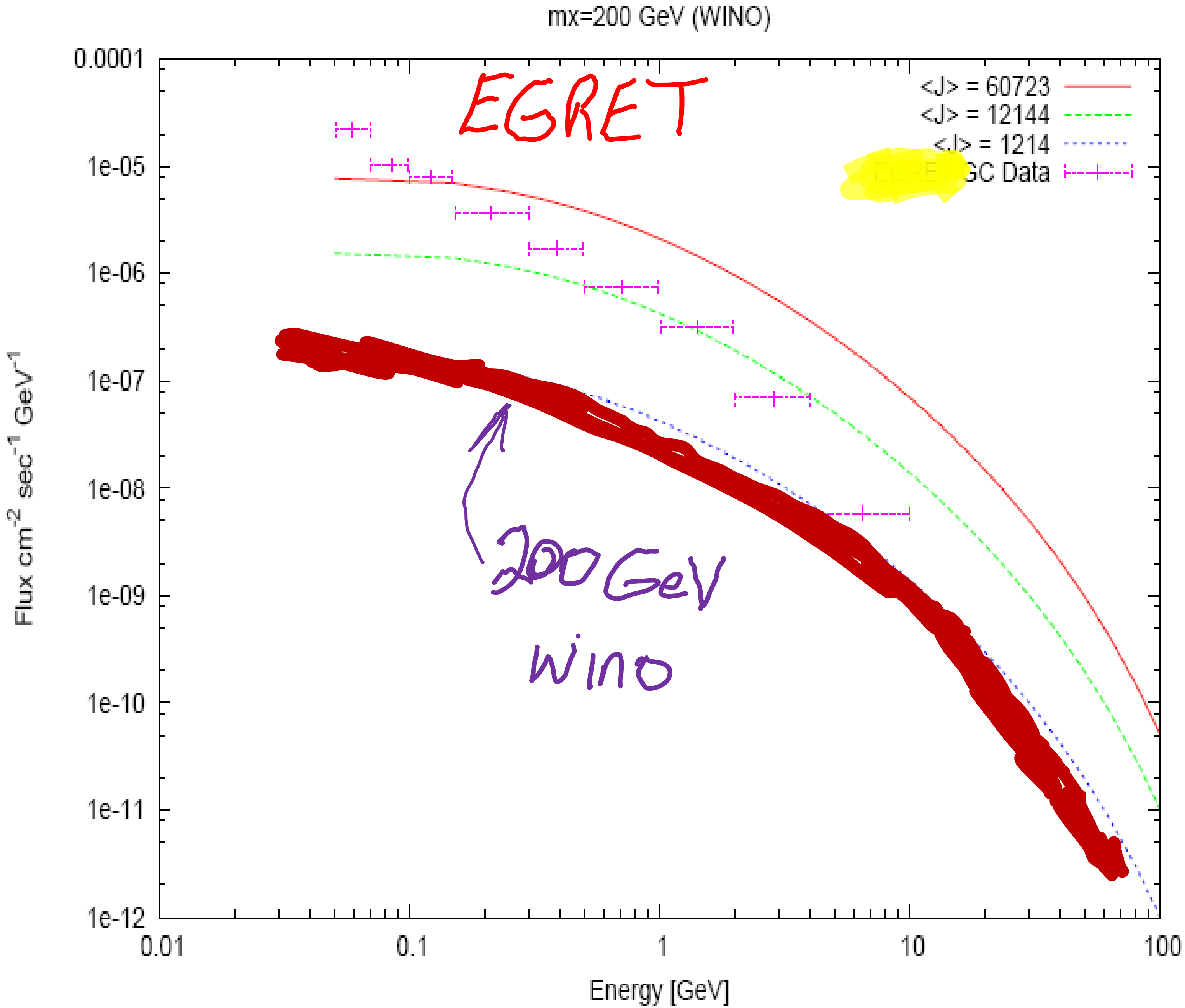
BESS 95 + 97
Background
Isothermal
NFW
Merritt
m_χ = 200 GeV
$\Phi_{\bar{p}}$ (1/(GeV m^2 s sr))
Kinetic Energy (GeV)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-1}
1
10
10^{2}
$\bar{p}$



Antiprotons imply $M_\chi \lesssim$ 200 GeV and profile little softer than NFW

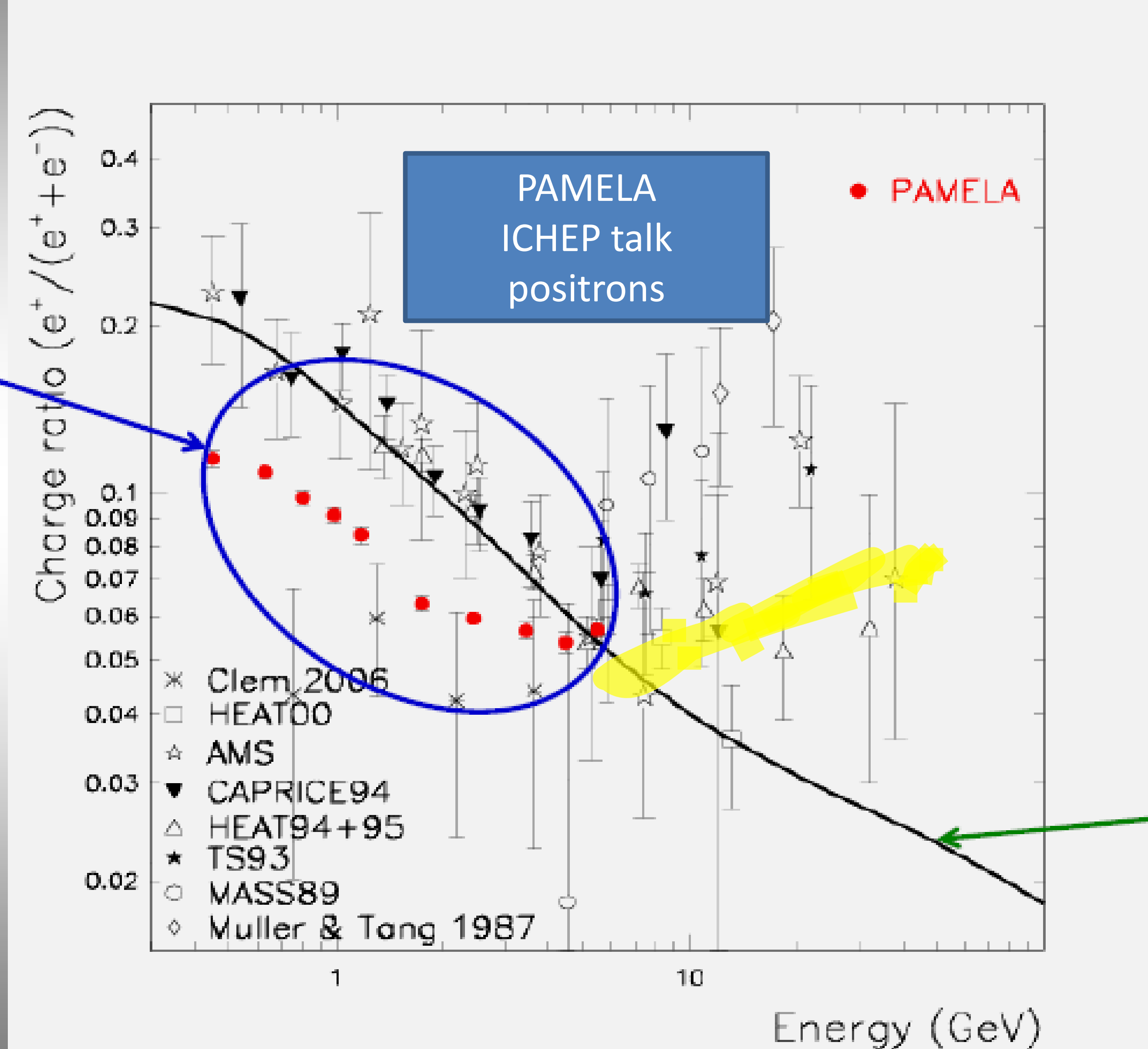
Antiproton-Proton Ratio





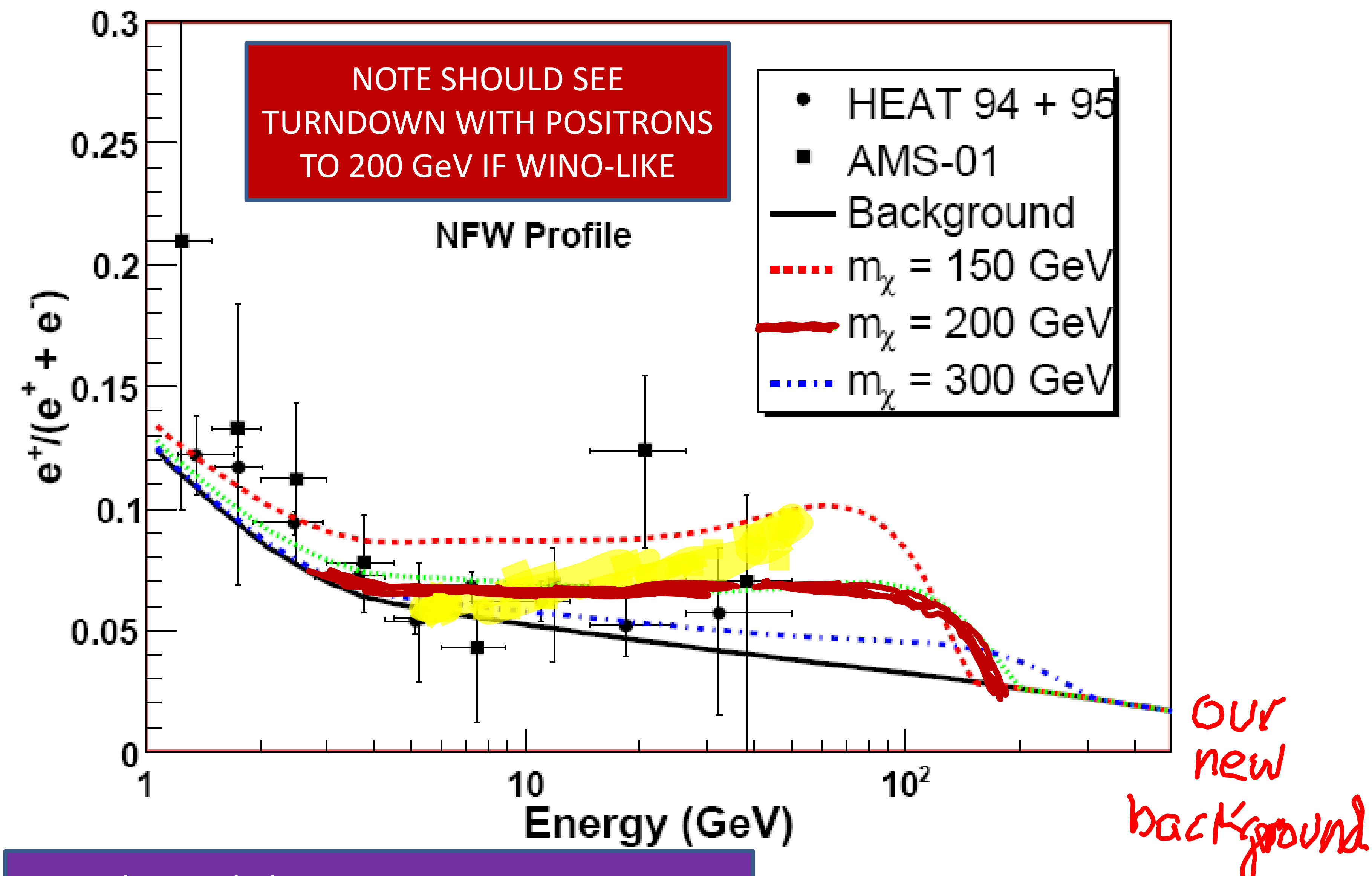
mx=200 GeV (WINO)
EGRET
<J> = 60723
<J> = 12144
<J> = 1214
EGRET GC Data
200 GeV
wino
Flux cm^-2 sec^-1 GeV^-1
Energy [GeV]
0.0001
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
10
100

Charge sign dependent solar modulation



nd 2007:
20 000
sitrons total

Positron data suggests $M_\chi \lesssim 200$ GeV



Grajek, GK, Phalen, Pierce, Watson 0807.1508

THUS we may be able to interpret the PAMELA data in a consistent way as a possible signal from galactic annihilation of a wino-like lightest superpartner if certain galactic properties hold,

-- e.g.

$$U_B / (U_B + U_{rad}) \approx 0.1$$

(but not 0.25)

-- DM profile somewhat softer than NFW

-- *etc*

-- our galactic parameters typically somewhat different from those of other authors, but as far as we can see ours are as reasonable

Note crucial role of data with higher energy positrons – must see turndown if wimp – good measure of mass

Pamela has data with positron energies up to $\sim$ 200 GeV in hand

AMS-02

GLAST

Launched June 11, awake

- Flux depends sensitively on detector angular resolution and on profile, so no EGRET conflict but likely GLAST signal
- Main source of gammas is pions from later stages of LSP decay
- (Could have monoenergetic gammas from box diagram, didn't look at that yet)
- Some confusion in literature, and all but last version of DARKSUSY – we don't agree with recent large GLAST survey Baltz et al
- For a 5 sigma signal in one year need minimum flux of 3x10^{-9} $cm^{-2}sec^{-1}$ (> 100 MeV)
- 200 GeV wino, NFW → 16x10^{-9} – so a 3 σ confirmation signal $\sim$ 2 months

- Other kinds of dark matter?

- Other conventional origin for positrons?

REST OF TALK

II. DAMA/Libre?

III. Normalize wino LSP abundance to local density? Calculate the relic density? → cosmology

IV. Tests for LHC? Learn DM properties from LHC?

II There has been another (controversial) hint of a dark matter signal – DAMA/LIBRA -- 7 years of checking systematics

Amazingly (or amusingly) under certain special conditions this is consistent with the PAMELA excess positrons -- GK, Aaron Pierce, Neal Weiner, in progress

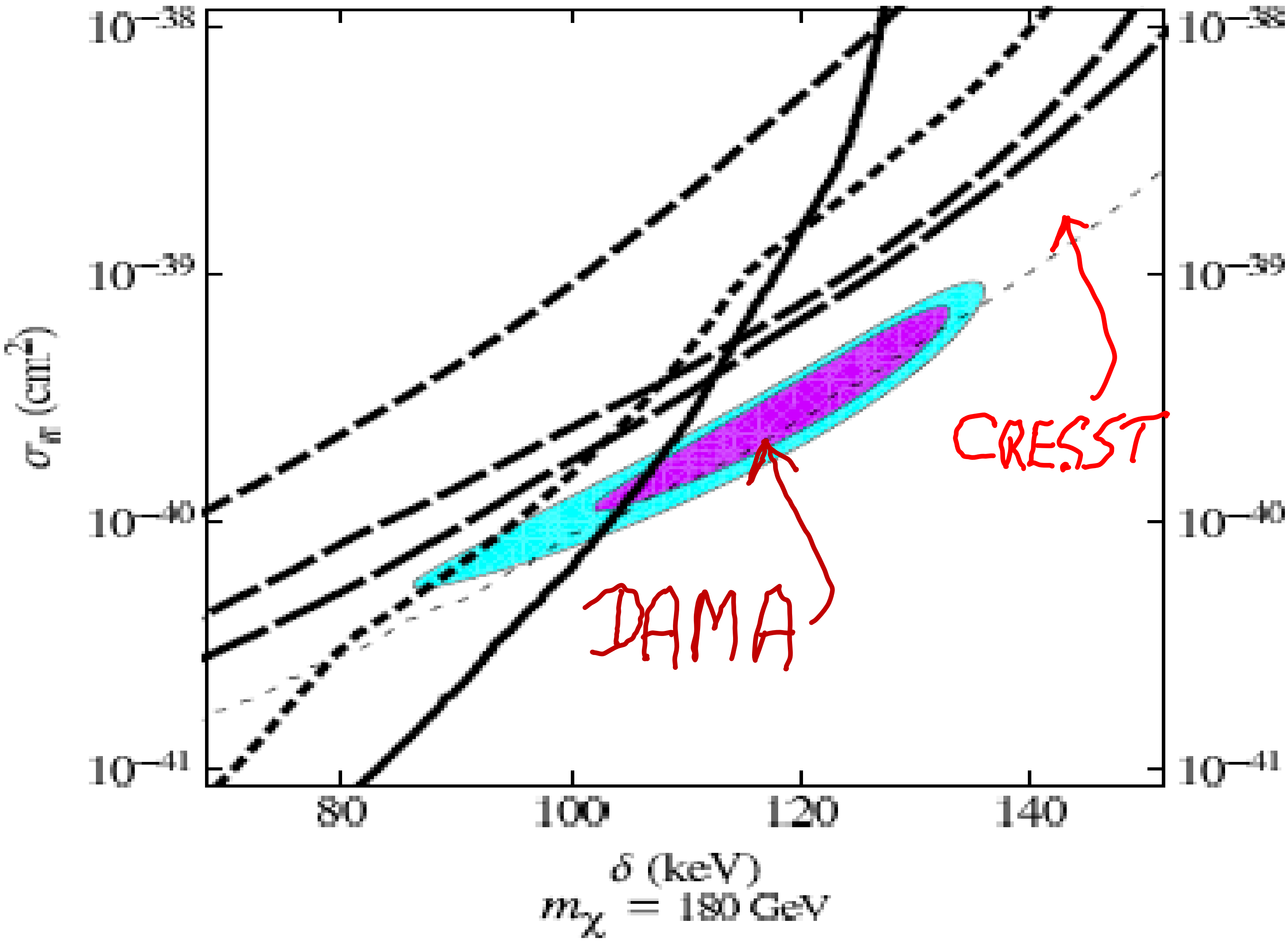
DAMA/LIBRA ANNUAL MODULATION?

- Null results from several other detectors
- Neal Weiner et al very special model (arXiv: 0807.2250 and earlier)

  -- in addition to χ there exists an excited state χ^* with mass splitting $\sim$ 100 KeV (similar to KE of WIMP in halo)

  -- elastic scattering $\chi N \rightarrow \chi N$ small compared to $\chi N \rightarrow \chi^* N$
- Then experiments mainly probe higher velocities of wimp halo distribution → expected modulation effect enhanced significantly, and low energy events are suppressed in spectrum
- Models exist that do this – Dirac fermion is comprised of two degenerate Majorana fermions – off diagonal vector coupling → “pseudodirac” fermion -- works for neutralinos in approximately R-symmetric supersymmetry – or for complex scalar such as sneutrino, with Z coupling off-diagonally between real and imaginary parts

Chang, Kribs, Tucker-Smith, Weiner arXiv:0807.2250



Same DM candidate as PAMELA excess?

Maybe!

Still checking constraints –

-- possible concern is annihilation in sun giving energetic neutrinos that Super-K would see – DAMA needs large cross section, so candidate might be captured efficiently by sun – but inelastic scattering larger off heavier nuclei, so capture rate is suppressed considerably for sun mainly made of H,He, so we think it is all right

III CONSIDER THE CONNECTIONS BETWEEN THE DARK MATTER CANDIDATE, ITS RELIC DENSITY, AND THE SIGNALS

[recent mini-review, GK and Scott Watson, ArXiv: 0807.2244]

- Traditionally, thermal equilibrium assumed as the universe cooled

$$\chi + \chi \leftrightarrow \gamma + \gamma,\ e^+ + e^-,\ \text{etc}$$

until universe too cool to make χ pair, so solve Boltzmann eq.

$$d(n_\chi a^3)/dt = -a^3 \langle \sigma_\chi v \rangle [n_\chi^2 - (n_\chi^{eq})^2]$$

And get

$$n_\chi = 3H(T_{freeze-out}) / \langle \sigma_\chi v \rangle$$

→ "wimp miracle"

"THERMAL"

- For typical weak interaction cross section, and $M\chi \sim 100$ GeV, get observed relic density

But

- Winos annihilate very well, so actually find only of order 5-10% of relic density for winos if this thermal equilbrium history holds – so if PAMELA indeed seeing wino-like LSP then it does not make up most of the relic density in a *thermal* history
- But to get enough positrons we assumed it did make up the full local relic density
- How well founded is the thermal history theoretically?
- Not very.

- More generally, is a thermal history what we would expect? Probably not.

We hope for an underlying theory that has inflation, baryogenesis, dark matter, electroweak symmetry breaking, etc

What happens in such theories?

Essentially never has thermal equilibrium history!

E.g. string theories contain "moduli", scalar fields that specify the sizes of small extra dimensions, and their quanta – the quanta are produced in the early universe, and decay into quarks, leptons, gauge bosons, squarks, gauginos, etc – their BR to superpartners is about 25%, and each one gives an LSP DM particle

-- in our study of M-theory compactified on a G_2 manifold, we found that most of the DM particles came from moduli decay!

Other non-thermal sources:

-- supersymmetric flat directions, Q-balls, increased expansion rate due to non-standard kinetic energy , cosmic strings, etc

Suppose many extra LSPs produced by moduli decays, fields relaxing, etc – then the LSPs will quickly annihilate down to the solution of the Boltzmann equation,

$$n_{\chi} = 3H(decay) / \langle \sigma_{\chi} v \rangle$$

So the "wimp miracle" is preserved – now the Hubble parameter is evaluated at a different temperature

So it is appropriate to decouple the relic density from the particle type when checking to see if a given type can describe a possible signal – so normalize the relic density to the local one when testing models

One would have to work very hard to construct theories that addressed inflation, baryogenesis, etc in which the relic density arises from the thermal equilibrium calculation

Then the relic density of a candidate must be calculated from measurements of its properties – need data from LHC, indirect measurements of positrons, antiprotons, gammas, synchrotron radiation, neutrinos from sun and earth – direct detection on different nuclei – and need cosmological history

IV. DARK MATTER AND THE LHC

Collider-friendly gluino mass

- Gluino mass few times LSP mass in models ($\sim$2 to $\sim$ 10)
- Assume indirect experiments suggest a DM candidate , e.g. PAMELA
- Hopefully LHC will detect new physics signals, with an associated DM candidate – a neutral particle escaping the detector in pairs
- Have to measure mass, properties to confirm same object in different experiments
- LHC not sufficient

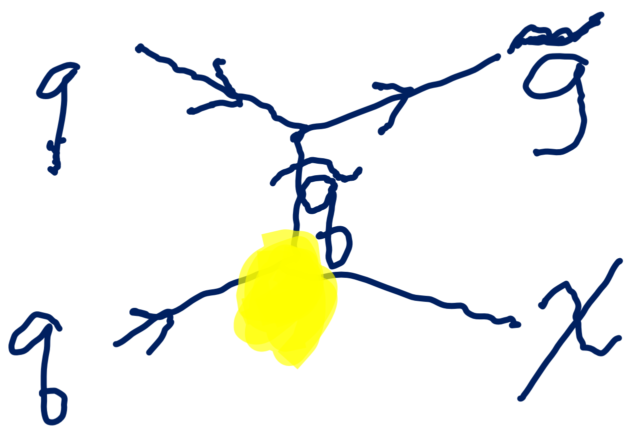
  -- need direct or indirect to establish lifetime $\sim$ universe

  -- need to know cosmology history to calculate relic density

  -- probably need to measure mass and couplings several ways to improve relic density calculation
- Assume supersymmetry is what is found, and LSP relic density calculation is the goal
- Detailed simulation studies beginning

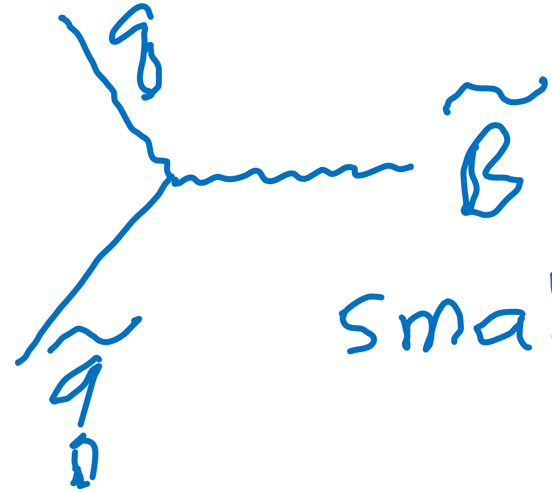
For now, assume for simplicity see wino signal in PAMELA

- χ mainly wino-higgsino mixture – need to know how much
- Assume gluino and squark (left- and right-handed) separately measured first
- Look at subdominant processes (not discovery channels) such as

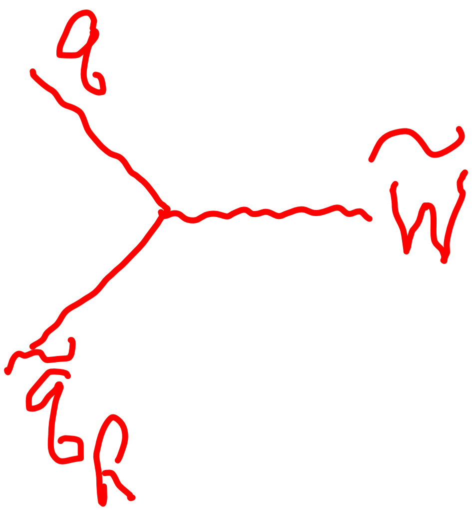


- If this is seen, there is little higgsino in the LSP – the actual cross section measures how much

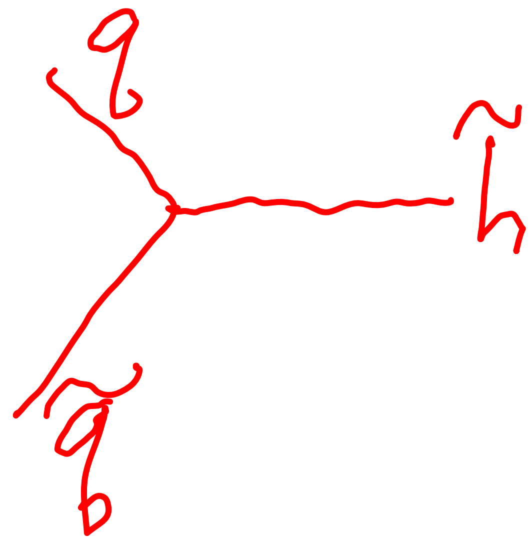
large,



smaller,



and



zero

- Also study associated neutralino – chargino channels
- Also use BR of gluino and squark decays – e.g. does gluino decay to quarks and first neutralino or second neutralino or chargino
- If see trilepton events then chargino and LSP are not degenerate and are mainly different type

Basic point – many LHC signatures depend on the composition and properties of the DM, so the LHC signatures ***will*** allow one to untangle the properties of the DM – no single process or measurement, but *combination of several* – both what is seen and what is not are important

Techniques exist using signature plots to carry out such analyses.

Then how should one proceed?

(A) Take models that are sufficiently complete to have a cosmological history, and electroweak symmetry breaking, and calculate the relic density in those – there will be several different ones that work, but all will have testable predictions

(B) Calculate the relic density as if it were thermal – then

-- could come out ***about right*** – then like (A)

-- could come out ***too small*** – then

(1) evidence for another source of DM, e.g. axions

(2) or DM was produced non-thermally

(3) or at the time the DM was produced the cosmic expansion was not radiation dominated

-- could come out ***too large*** –then

(1) must be additional sources of late entropy

(2) or late inflation reduced it

In all cases learn from LHC about DM and about cosmological history!

CONCLUSIONS?

NOT YET – QUESTIONS AND TESTS

MCTP WORKSHOP, LHC AND DARK MATTER, January 6-9, 2009

Ann Arbor, Michigan (google mctp)

Organizing committee: Binetruy, Freese, Gianotti, Lykken, Kane, Pierce, Spiropulu, Watson, Wang