THEORY OF DARK MATTER

Graciela Gelmini - UCLA

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Content:

- Dark Matter: what we know
- WIMPs: earliest relics
- New physicS at the EW scales?
- Burst of recent model building to account for hints of DM in Direct and Indirect searches: present hints and some models
- "A theory of DM"?
- Summary and conclusions

Dark Matter: We know a lot!

- We know its abundance in the Universe to a percent level: $\Omega_{DM} = 23.2 \pm 1.3\%$

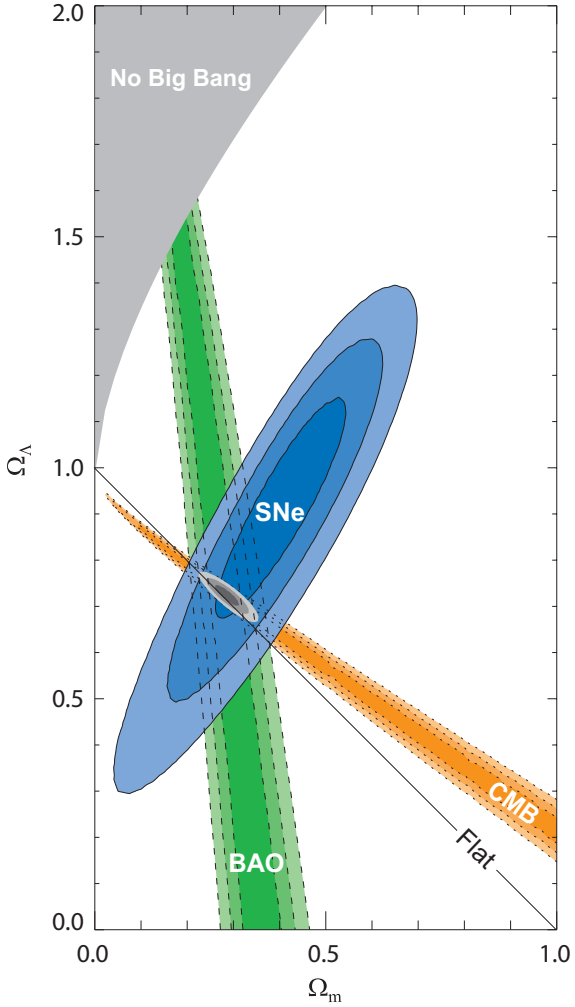
- We know most of it is not in MACHOS (Macroscopic Astrophysical Halo Objects): $m_{DM} < 10^{-7} M_{\odot} \simeq 0.1 M_{\rm Earth}$ so... probably EP?

- We know most is not baryonic

- We know is it NOT explained by the Standard Model of EP

Dark Matter: not baryons

Fig: Kowalski et al 2008



$\Omega = \rho/\rho_c \qquad \rho_c \simeq 5\ \mathrm{keV/cm^3}$

68.3%, 95.4%, 99.7%CL constraints on Ω_M and Ω_Λ obtained from Cosmic Background Radiation Anisotropy CMB (orange), Baryon Acoustic Oscillations BAO (green), and the Union Compilation of 307 Type Ia supernovae (SNe Ia) (blue); Ω_m $=0.285^{+0.020}_{-0.019}(\mathrm{stat})^{+0.011}_{-0.011}(\mathrm{sys})$ assuming DE is a cosmological constant

WMAP7, BAO, SN1a: E. Komatsu, et al., 2010

$\Omega_\Lambda = 72.2 \pm 1.5\%$ $\Omega_m = 27.8 \pm 1.5\%$

where Ω_m is:

$\Omega_b = 4.61 \pm 0.15\%$ $\Omega_{DM} = 23.2 \pm 1.3\%$

Most of the Dark Matter: is cold or warm namely is non-relativistic or semi-relativistic at galaxy formation ($T \simeq 1\mathrm{keV}$)

No CDM or WDM in the SM! (active-ν are HDM)

But many in extensions of the SM!

- Warm dark matter: sterile neutrino, gravitino, non-thermal WIMPs...
- Cold dark matter: WIMPs (LSP or variants LKP, LZP, LTP), axion, WIMPZILLAs, solitons (Q-balls), SuperWIMPs (get their relic density from WIMPs which decay into them)...

Why WIMP's? The "WIMP" miracle....

WIMPs as Dark Matter: "Thermal WIMPs"

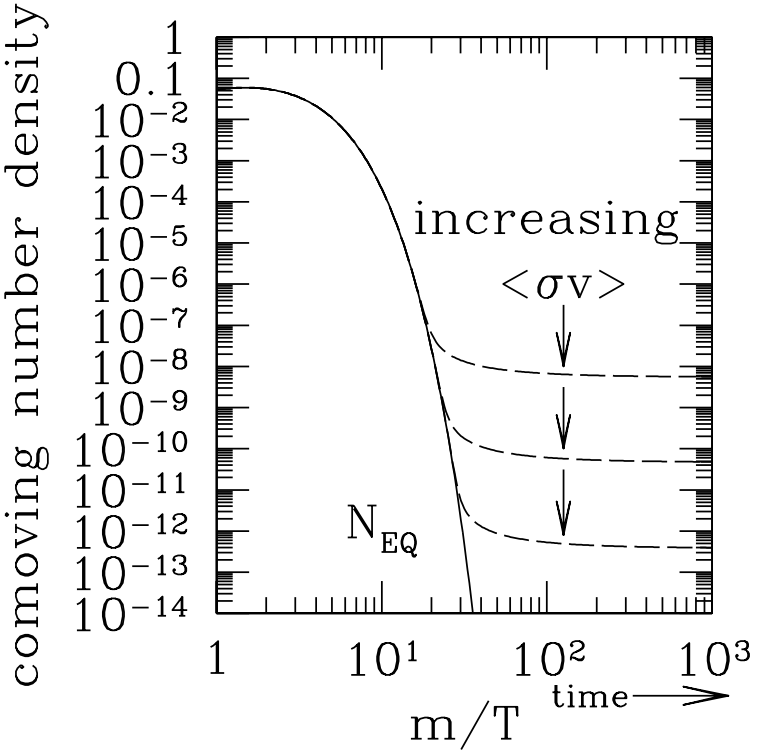
WIMPs are the earliest relics, from the pre-BBN era of the Universe, from which we have no data! So we must make assumptions...

Standard Assumptions: Universe radiation dominated at $T > T_{f.o.} \simeq m/20$

- WIMPs reach thermal equilibrium while radiation dominates
- Chemical decoupling when $\Gamma_{\rm ann} = \langle \sigma_{annih} v \rangle \, n \leq H$,
- No entropy change in matter+radiation

$$\Omega_{\rm std} h^2 \approx 0.1 \, \frac{3 \times 10^{-26} {\rm cm}^3/{\rm s}}{\langle \sigma v \rangle}$$

Weak $\sigma_{annih} \simeq 3 \times 10^{-26} {\rm cm}^3/{\rm s}$ for $\Omega h^2 = \Omega_{DM} h^2 \sim 0.1$!



We do not know the history of the Universe before BBN

we expect to learn about it precisely from WIMPs (or sterile neutrinos..., relics from that epoch)

- Earliest remnants: WIMPs decouple at $T_{f.o.} \simeq m_\chi/20$

- BBN (ends at $t_U \simeq 200$ sec, $T \simeq$ MeV) is the earliest episode from which we have a trace: the abundance of light elements D, ^{4}He, ^{7}Li.

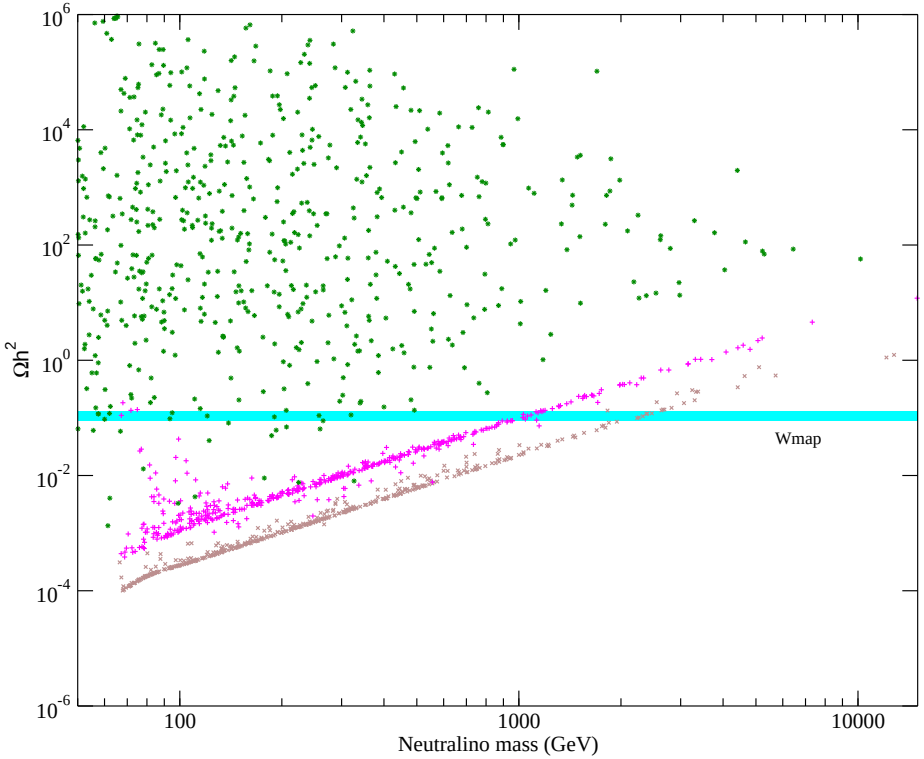
  Imposes only $T_{RH} > 4$ MeV Hannestad, 2004

  T_{RH}: highest T of the radiation dominated epoch before BBN

- In many viable non standard cosmological models relic densities may be very different, e.g. Low T_{RH} Models (have two additional parameters T_{RH} and η)

$\Omega_\chi^{\rm std} = \Omega_{\rm DM}$: Very constraining on models!

e.g. neutralinos in MSSM after LEP-II



- bino-like: OVERDENSE of fine-tuned
- higgsino-like: UNDERDENSE

(or $m \simeq 1$TeV-beyond LHC)

- wino-like: UNDERDENSE

(or $m \simeq 2$ TeV-beyond LHC)

.

Need Well Tempered Neutralinos

at boundary bino/higssino or bino/wino

$M_1 = \pm\mu$ or $|M_1| = |M_2|$

(Arkani-Hamed, Delgado, Giudice, 2006)

e.g. 1700 models, MSSM with 9 parameters + μ sign G.G., Gondolo,Soldatenko and Yaguna, 06

Same MSSM- non standard pre-BBN cosmology

Same 1700 models

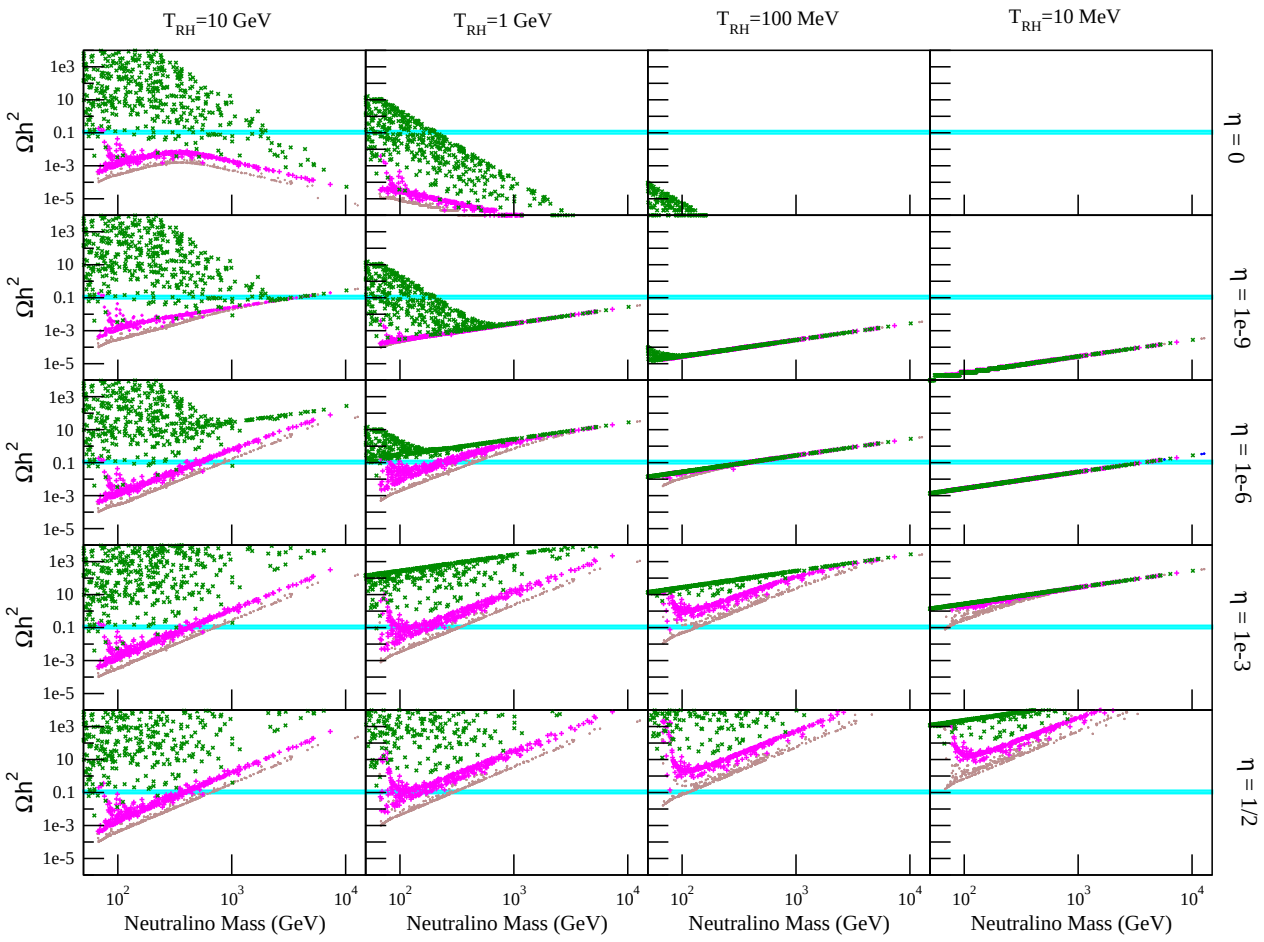
G.G., Gondolo, Soldatenko and Yaguna, 2006

All points can be brought to cross the DM cyan line with suited T_{RH}, η

bino-like

higgsino-like

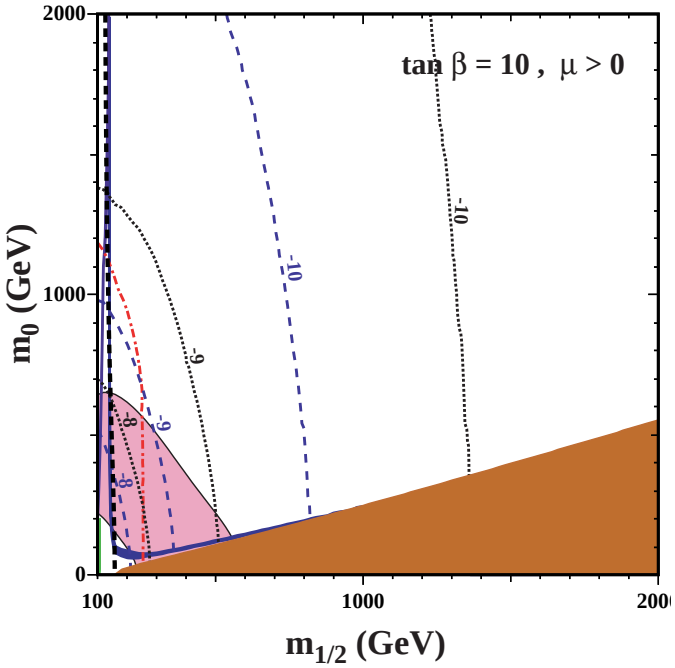
wino-like

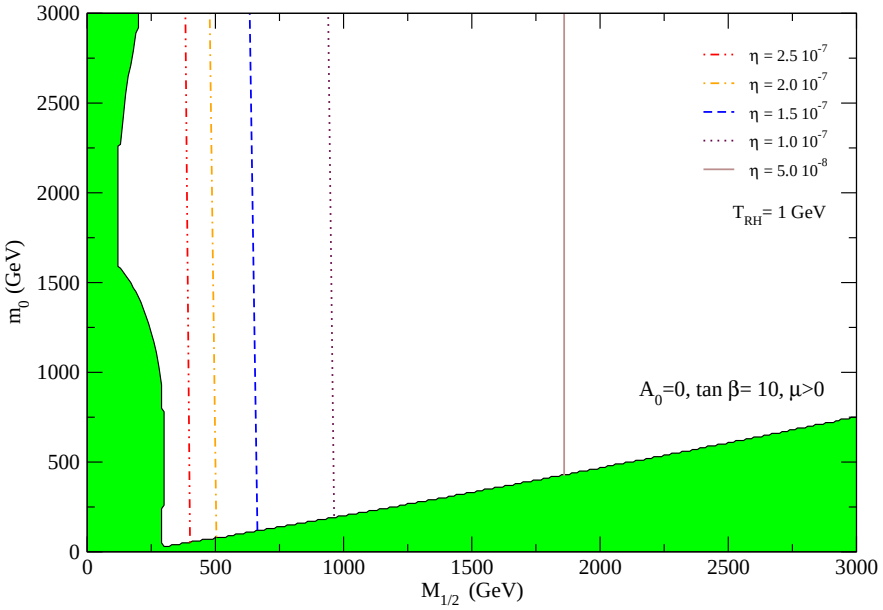


DM constraint: std vs non-std pre BBN cosmology

e.g. neutralinos in CMSSM are the DM only in the blue narrow bands

(e.g. J. Ellis et.al.2005)





In most of the parameter space WIMPs are overdense, thus models rejected!?

NO, since relic abundance depends on assumptions on the pre-BBN era!

The narrow band can be anywhere in the parameter space, if right T_{RH}, η

New physics at the EW scale

Expected because of Spontaneous Symmetry Breaking arguments (totally independently of the DM issue)

Naturalness implies $\Lambda_{SM} \approx \mathrm{O(TeV)}$ above which the cancellation in corrections to m_{Higgs} is due to a new theory....

- supersymmetry (with or without a composite Higgs boson)
- technicolor (walking or top assisted TC)
- large extra spatial dimension (possibly warped)
- "Little Higgs" model (Higgs is a pseudo-Goldstone boson)

which provides main potential discoveries at the LHC

and DM candidates...mostly WIMPs: LSP, Lightest Technibaryon, LKP (Lightest KK Particle) or LZP (in Warped SO(10) with Z3 model), LTP (the Lightest T-odd heavy photon in Little Higgs with T-parity)...

New physics to explain DM?

May be different...., for example Arkani-Hamed, Finkbeiner, Slatyer and Weiner 0810.0713

"A Theory of DM" WIMP, with 500-800 GeV mass, has an exited state with mass difference 0.1 to 1 MeV, is charged under a broken hidden gauge symmetry G_{dark} with a boson ϕ lighter than 1GeV, explaining:

- the INTEGRAL data with "exciting" (XDM)
- the ATIC (now not found by Fermi!) and PAMELA data
- the WMAP Haze and the EGRET excess (now not found by Fermi!)
- the DAMA signal with "inelastic" (IDM)

Attests to the ingenuity of theorists to explain everything.....

Made to fit DM-not to solve the EW hierarchy.... and provides signatures for the LHC: major additions to SUSY signals, GeV-dark Higgses and gauge bosons decay into visible particles and leptons, MSSM LSP decays into the true LSP, thus many lepton jets with GeV invariant masses expected...Arkani-Hamed, Weiner 0810.0714 [hep-ph]

Physics beyond the SM

is required by Dark Matter,

and expected at the EW scale,

and both physics may or

may not be related!

Thus LHC and DM searches are

independent and complementary.

DM searches:

Complementary to the LHC and to each other!

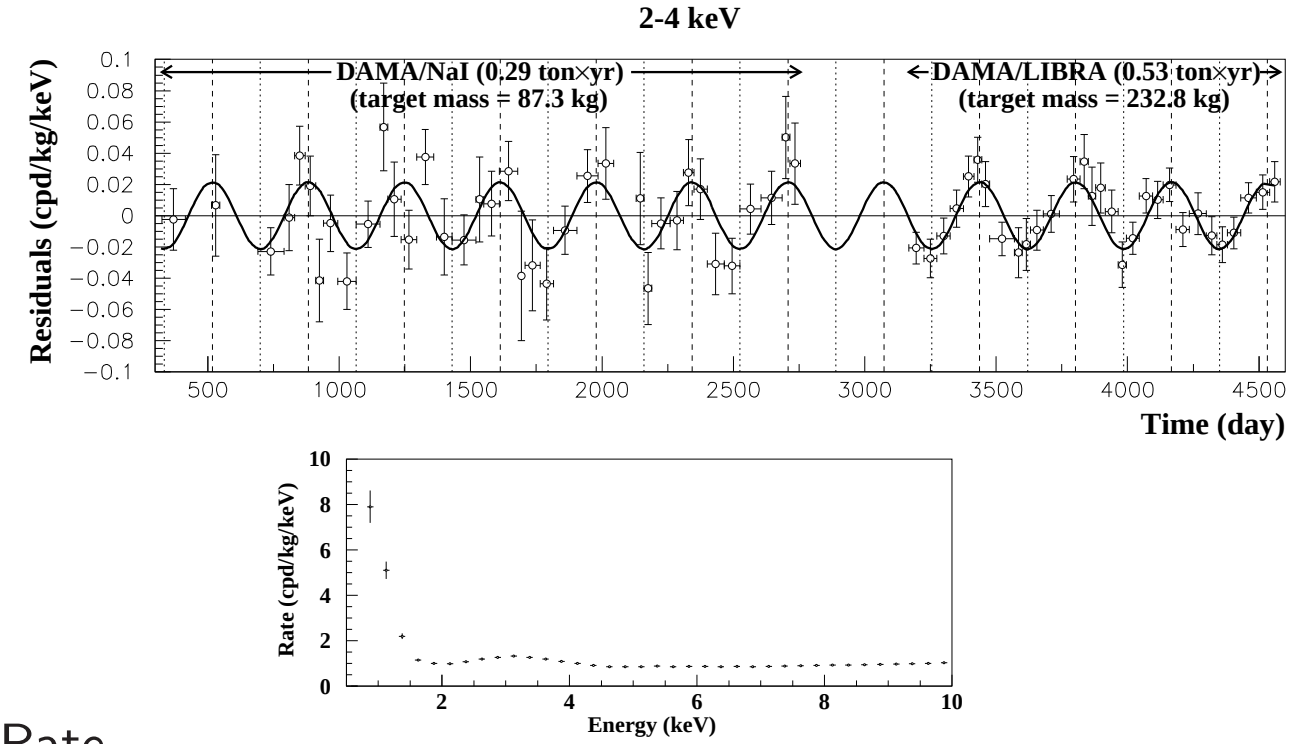
- Direct Detection- looks for energy deposited within a detector by the DM particles in the Dark Halo of the Milky Way
  Signature: same σ and m + annual modulation and/or recoil direction, seen by different experiments with different nuclei
  (Many: CDMS, XENON, DAMA, Edelweiss, Cresst, Zeplin, LUX...)
  (talk of Laura Baudis)

- Indirect Detection- looks for DM annihilation (or decay) products
  Signature: no other possible sources or complementary to other searches
  - neutrinos from Sun/Earth or the GC (AMANDA-Icecube, Antares-KM3NeT)
  - γ-rays and anomalous cosmic rays from Galactic Halo(s), and the Galactic Center (FST, HESS, VERITAS, PAMELA, ATIC, AMS...) (talk of Werner Hoffman)

DM-searches+LHC: all is possible!

- LHC sees many new particles and the DM particle mass range, which is simultaneously detected in Direct/Indirect Searches (e.g. MSSM neutralino?)
- LHC sees many new particles and finds the NLSP, DM searches cannot detect the LSP (e.g. it is the gravitino in a "SuperWIMP" model)
- LHC finds only the Higgs, but DM is detected in Direct/Indirect DM Searches (e.g. Split-SUSY, Inert Doublet Model?- push most particles besides the lightest Higgs and the DM candidate to high energies where LHC cannot see them)
- LHC sees new physics but DM is not related to it (e.g. axions, sterile neutrinos)
- Any other combination you may imagine...

Direct DM Searches: DAMA/LIBRA 25 NaI (Tl) crystal of 9.5 kg each, 4y in LIBRA (11 years total), 0.83 ton $\times$ year, 8.2σ modulation signal.



Rate

Direct DM Searches: is the DAMA/LIBRA annual modulation signal compatible with all other searches?:

maybe inelastically scattering and light WIMPs among others

Inelastic DM (IDM): Tucker-Smith, Weiner 01 and 04; Chang, Kribs, Tucker-Smith, Weiner 08; March-Russel, McCabe, McCullough 08; Cui, Morrisey, Poland, Randall 09

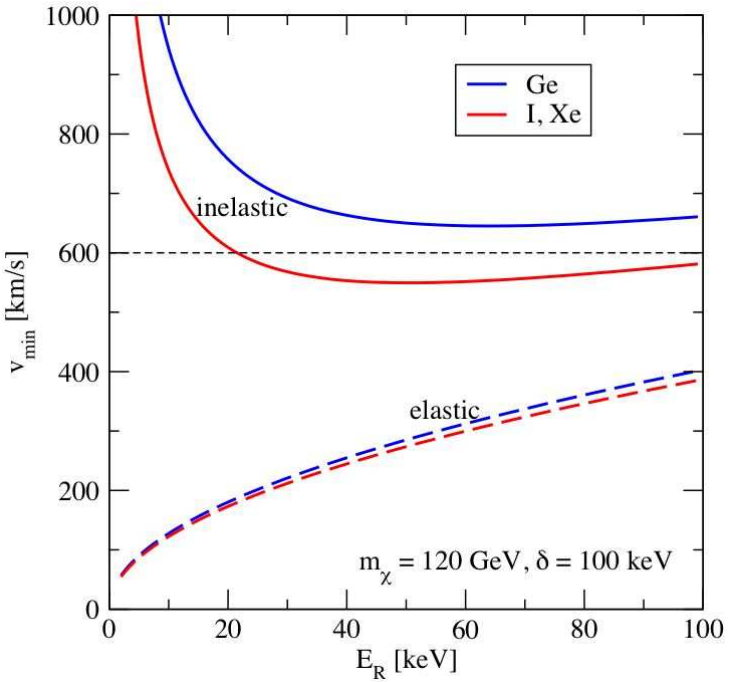
In addition to the DM state χ with mass m_χ there is an excited state χ^*

$$m_\chi - m_{\chi^*} = \delta \simeq 100 \text{ keV}$$

Inelastic scattering $\chi + N \to \chi^* + N$ dominates over elastic.

Models: a quasi Dirac fermion (Dirac mass >> Majorana mass, leads to a splitting and a gauge boson coupled to two different mass eigenstates), or similar to the p and n and their coupling to the W (but in a hidden sector)

Inelastic DM (fig from T. Schwetz)

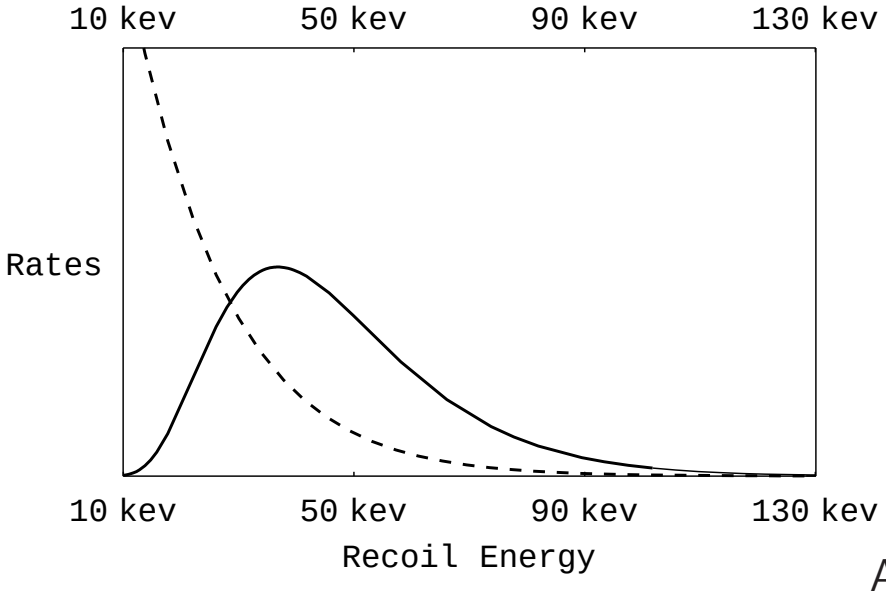


$$v_{min}^{inel} = \sqrt{\frac{ME_R}{2\mu^2}} + \frac{\delta}{\sqrt{2ME_R}}$$

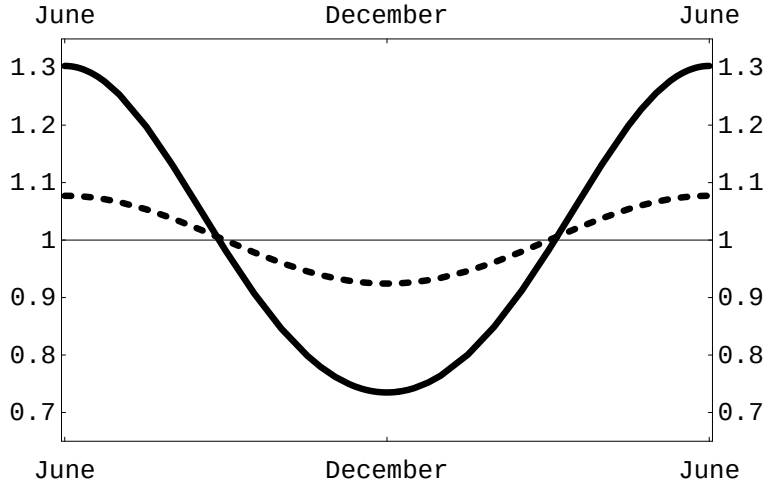
$$v_{min}^{el} = \sqrt{\frac{ME_R}{2\mu^2}}$$

Only high-velocity DM particles have enough energy to up-scatter, and v_{min}^{inel} decreases with increasing target mass M, thus targets with high mass are favored (better I in DAMA than Ge in CDMS, but Xe and W are heavy too...). Notice no low E_R events.

Inelastic DM Tucker-Smith, Weiner 04 $m_\chi = 50\text{GeV}$, $\delta = 100\text{keV}$



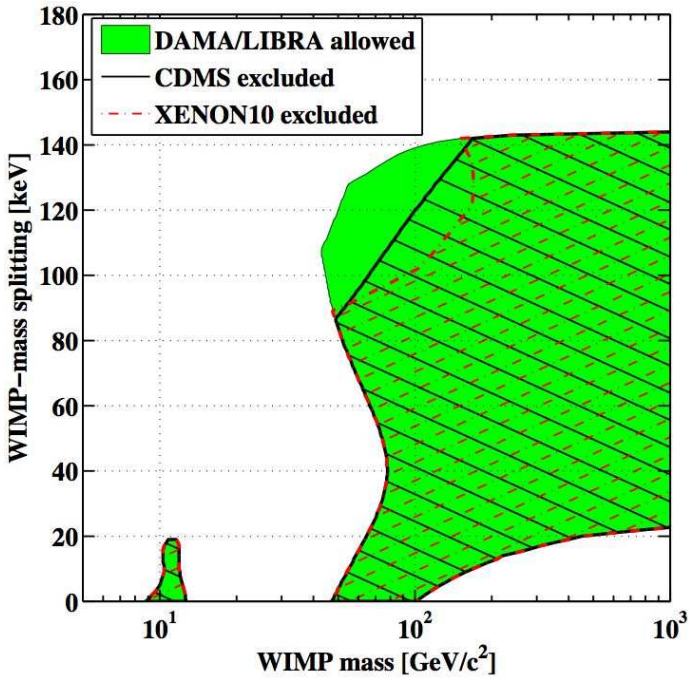
Spectrum in Ge



Annual modulation: elastic (dashed) and inelastic (solid)

Leads to very different spectrum (no low E_R events) The modulation of the signal is enhanced (the number of WIMPs changes more rapidly at high v)

IDM: for SI recent bound from CDMS leave very small room for compatibility



New XENON100 and 10 (lower thresh.) soon... this is for Spin Independent (SI) interactions

But IDM with Spin Dependent coupling to p would survive: Kopp, Schwetz, Zupan, 0912.4264; Chang, Liu, Pierce, Weiner &Yavin 1004.0697

- SD coupling with p,

eliminates XENON, CDMS and CRESST bounds

- Inelasticity,

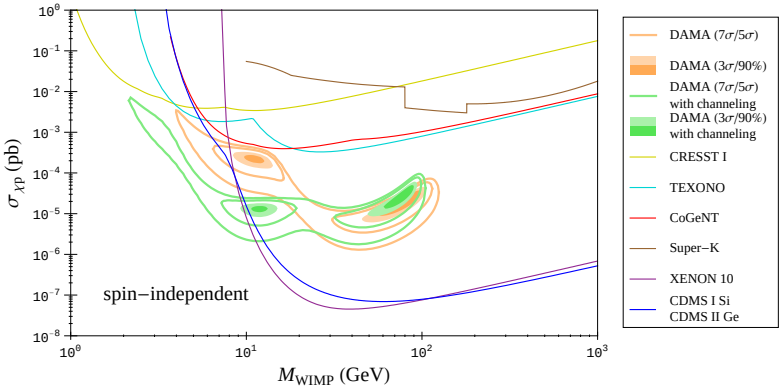
eliminates PICASSO and COUPP (light targets)

(For SD,coupling with nucleus is mainly with an unpaired nucleon:
- DAMA, KIMS , COUPP, PICASSO and SIMPLE have unpaired p,
- XENON, ZEPLIN,CDMS and CoGeNT have unpaired n)

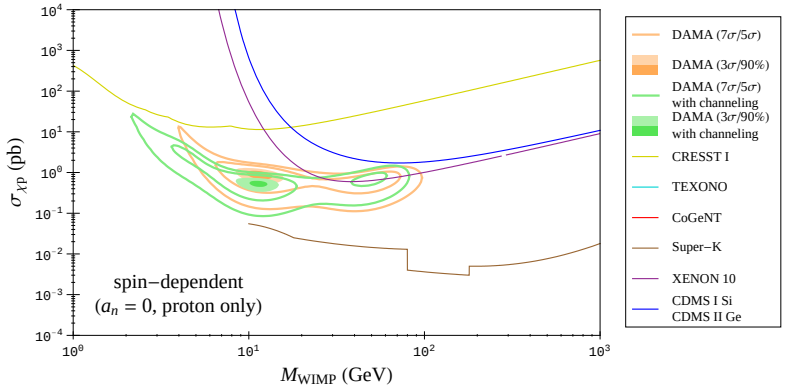
Light m <10 GeV WIMP's : Gelmini &Gondolo, 2004, 2005, Freese, Gondolo, Savage 2005

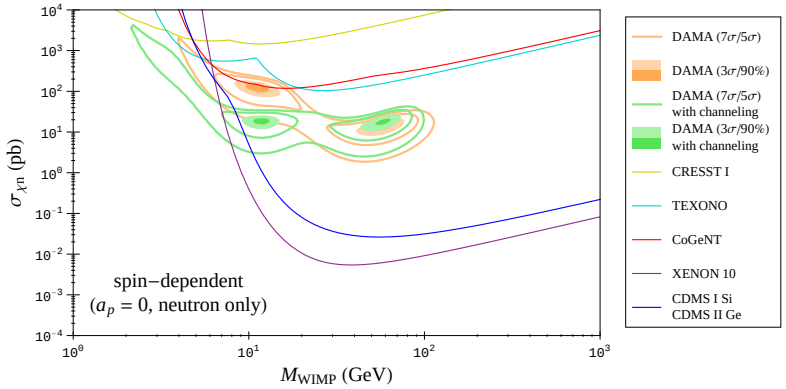
e.g. Savage,Gelmini, Gondolo, Freese JCAP 0904:010,2009

36 bins likelihood ratio 4 param. fits



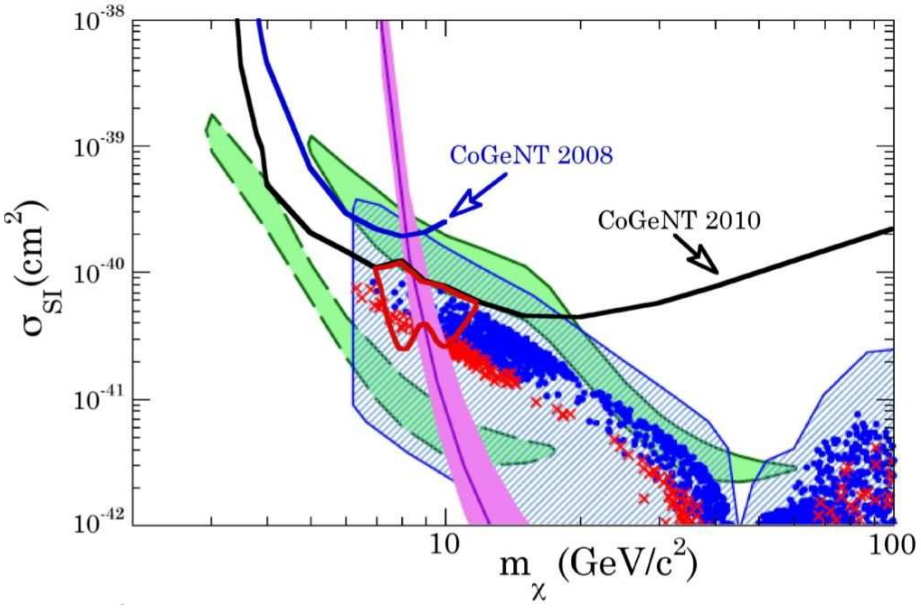
With large channeling effect, light usual WIMPs, $m \simeq$ 7 to 10 GeV were still a possible explanation (in conflict with CDMS and XENON at the 2-3σ level)





Recent reevaluation of channeling fraction: not important at less than 5σ- more difficult for light WIMPs Bozorgnia, Gelmini, Gondolo; Savage et al. 10

Light m <10 GeV WIMP's : DAMA+ recent excess of events by the CoGeNT collaboration (maybe also also hints in CRESST) generated a new bust of models, most need light bosons with GeV mass scale ... e.g.Chang, Liu, Pierce, Weiner &Yavin 10, Kufflic, Pierce & Zurek, 10; Essig, Schuster, Toro & Wojtsekhowski, 10



C. E. Aalseth et al. [CoGeNT collaboration], arXiv:1002.4703 [astro-ph.CO]

Indirect DM Searches: round of WIMP signals?

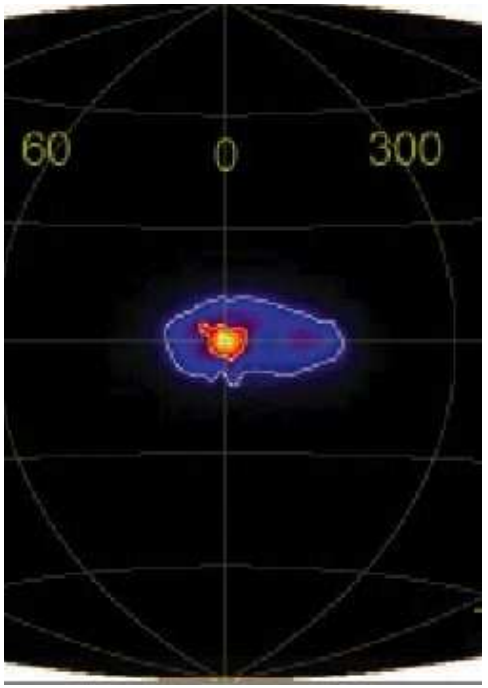
- CANGAROO, VERITAS, HESS 0.2-10 TeV γ's from the GC
  Found by HESS in 2006 NOT DUE TO DM (DM $<$ 10%)(PRL97, 221102, 2006)
  It is a background for FERMI observation of the GC Zaharijas, Hooper 2006
- EGRET excess in 1-10 GeV diffuse γ's (80 GeV WIMP annihilation?)
  REJECTED BY FERMI
- INTEGRAL 511 keV line from the GC (30 y old)
  Jan 2008: region not spherical but deformed towards LMXB!
  SO NO DM AFTER ALL? YES TO ACCOUNT FOR SPHERICAL COMPONENT?
- "WMAP haze" at the GC TO BE CHECKED BY PLANCK Finkbeiner et al. 2004
  Most WIMP models explain it as synchrotron from e e^+ produced in annihilations
  Hooper Zaharijas Finkbeiner and Dobler; astro-ph/0709.3114; Cholis, Goodenough and Weiner; arXiv:0802.2922
- PAMELA $e^+/(e^+ + e^-)$ excess from the halo
- and ATIC $(e^+ + e^-)$ excess from the halo REJECTED BY FERMI and HESS
- FERMI $(e^+ + e^-)$ excess over conventional diffuse model

INTEGRAL: 20 keV to 8 MeV, satellite launched in 2002
511 keV line from the GC, observed first with balloons (30 y old signal)
until recently region was seen as spherical pointing towards DM

Jan 2008: region not spherical but with a disk around Low Mass X-ray Binaries, which are possible sources of e! so no DM after all?

Still DM could explain the spherical component of the signal

Tuned DM candidates were proposed...



Models for INTEGRAL 511 keV line from the GC: Tuned DM particles were proposed. The positrons need to annihilate almost at rest to produce a line with $E = m_e$.

-MeV mass Light DM (LDM)(Boehm et al 04, Beacom et al 04)

The MeV scale is the mass of the annihilating DM particles, which annihilated into e^+e^-

- eXciting DM (XDM): (D. Finkbeiner 2007)

500 GeV mass χ with a excited state χ^* very close in energy

Similar to "Inelastic DM" proposed to explain DAMA/LIBRA, but
$\delta = m_{\chi^*} - m_\chi \sim$ MeV must be larger (not 100 keV but MeV)
so that e^+e^- are produced at rest via de-excitation of the excited state: $\chi^* \to \chi e^+e^-$.

The excitation of the high energy state is due to collisions, which fixes the particle mass, given the characteristic $v \simeq 10^{-3}c$:

$$E_{colllision} \simeq m_{\chi^*} - m_\chi \simeq (1/2)m_\chi 10^{-6} \simeq 1 \text{ MeV}$$

which works if $m_\chi \simeq 500$ GeV.

Graciela Gelmini-UCLA

"WMAP-Haze"

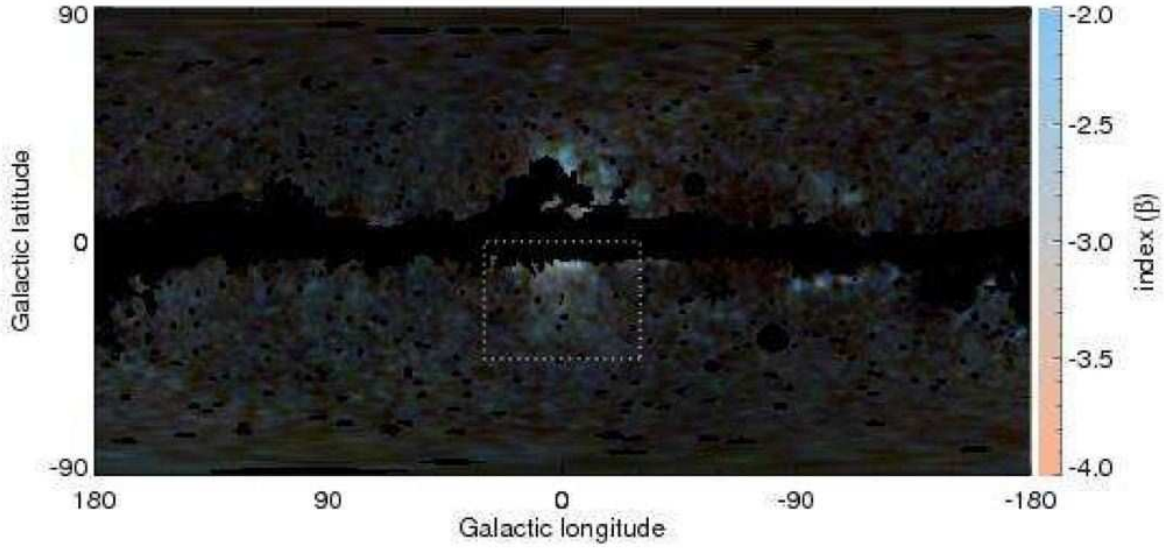


FIG. 7.— An RGB representation of $\mathbf{r}_H$ and $\mathbf{r}_{H+S}$ for RG8 with CMB5. The color coding indicates the spectral index, β, of antenna temperature, of a given pixel. In particular, the bluer haze region (*box*) indicates a harder spectrum than the redder synchrotron emission.

Dobler, Finkbeiner 2007

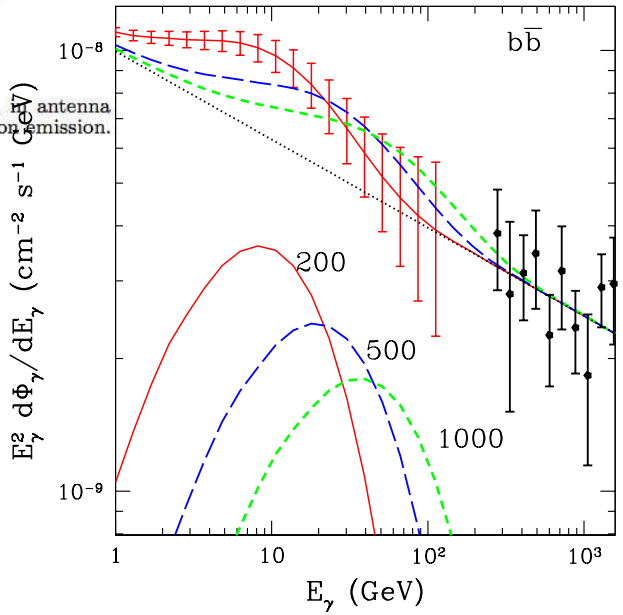
Not a result of the WMAP collaboration!

Almost any WIMP could produce it!

(synchrotron radiation of e^+ e^-)

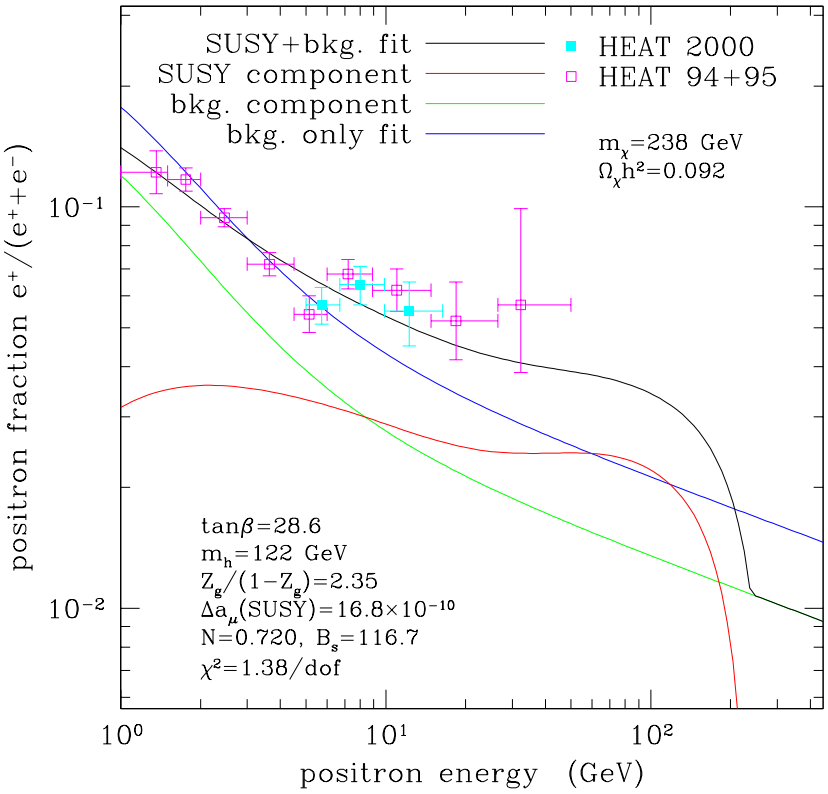
The new CMB satellite PLANCK data should find it or reject it!

Red faked GLAST data Hooper et al 2007



WIMP DM already seen?! The old "HEAT positron excess"

Baltz et al 2002;



Two explanations:

1) DM annihilation,
with boost factor $B > 30$

NOTICE: needed "Boost Factor" B

$$B = \frac{\text{Annihilation Rate Needed}}{\text{Naive Annihilation Rate}}$$

2) astrophysical sources

PAMELA: (Payload for Antimatter Exploration and Light-nuclei Astrophysics)

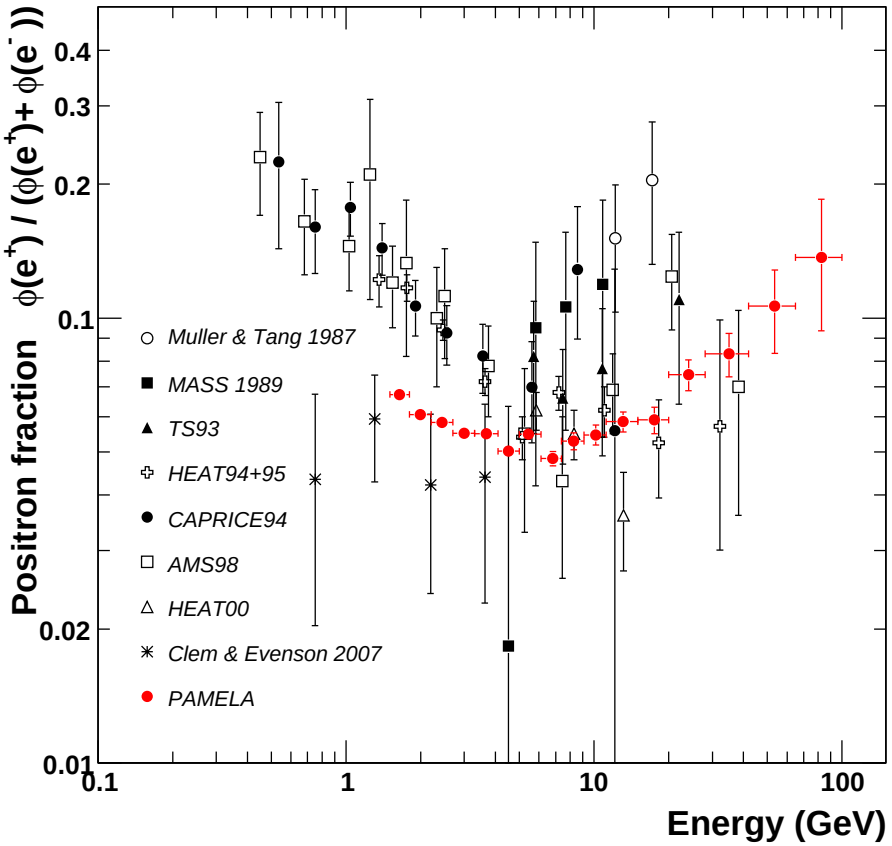
Magnetic spectrometer in orbit.

Launched in June 2006.

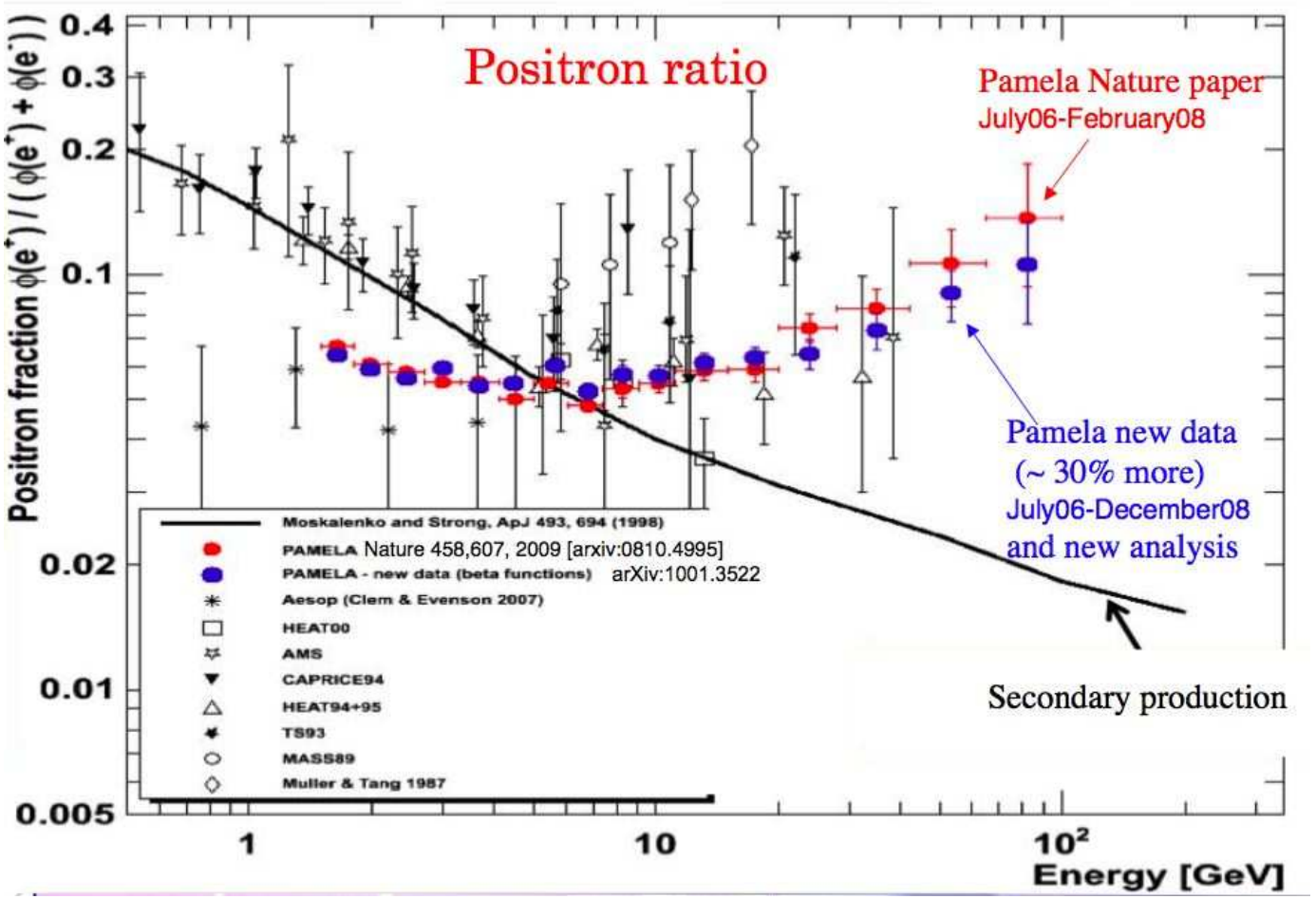
First data released in 2008.

Solar modulation effects important at $E < 10$ GeV

e^+-fraction excess at 10-100 GeV (Aug/08)!



PAMELA: Positron fraction excess 10-100 GeV



Also ATIC: (Advanced Thin Ionization Calorimeter instrument)

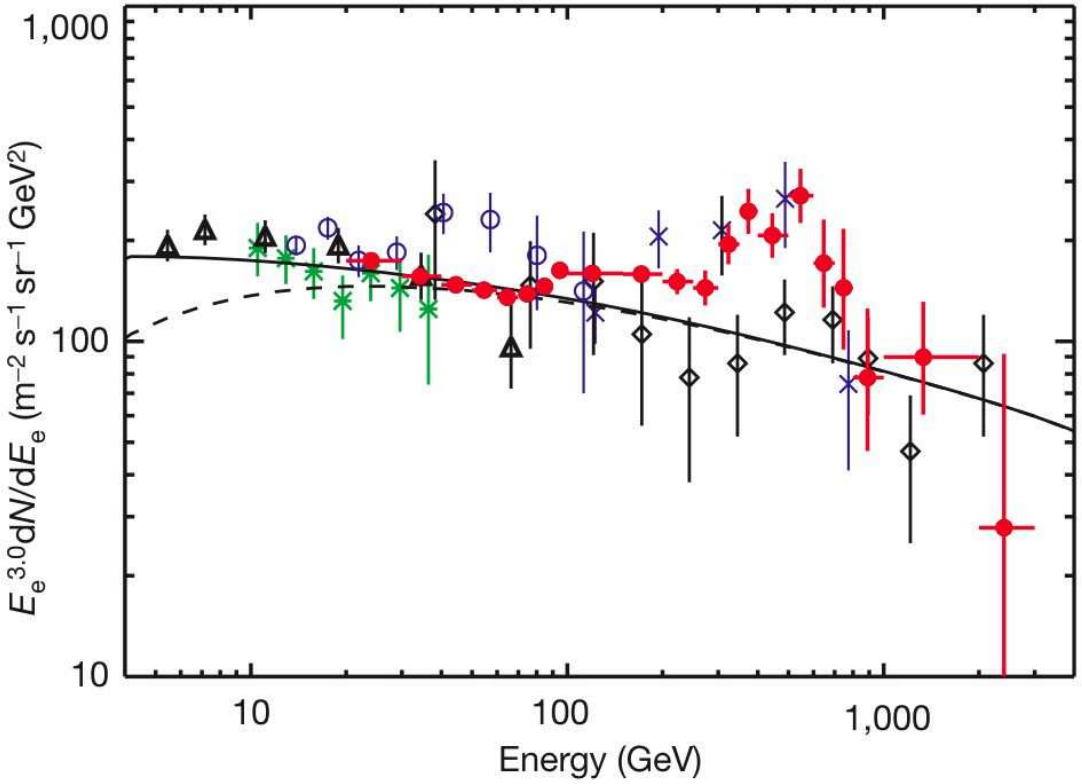
Balloon-born calorimeter launched

from McMurdo, Antarctica.

ATIC-1 in 2000-01

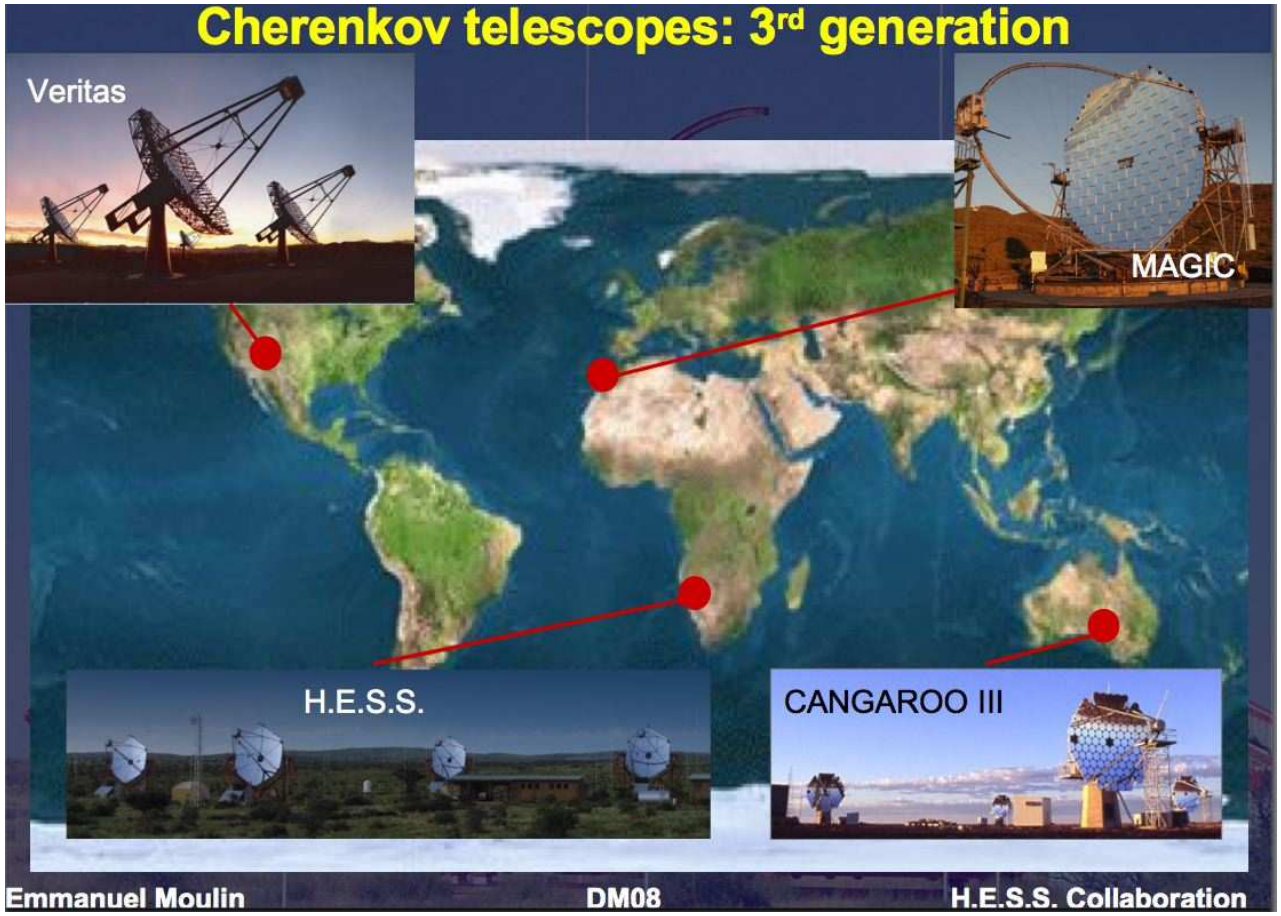
ATIC-2 in 2002-03.

Nature, Nov. 19, 2008
($e^+ + e^-$) 6σ excess in the
300-800 GeV range!



Confirmed by ATIC-4 (207-08) but rejected by FERMI and HESS

Air Cherenkov Telescopes (ACT's)



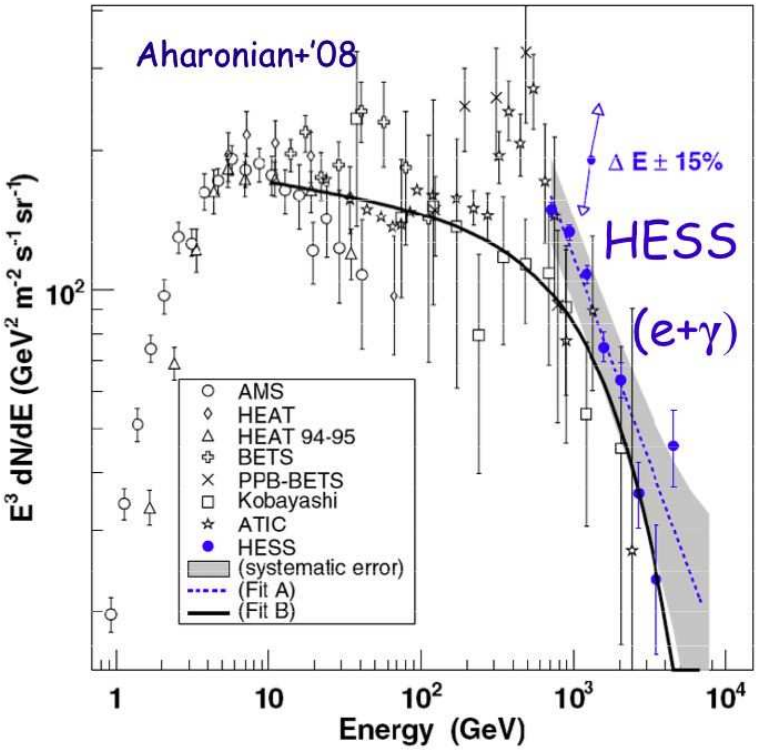
HESS: measures (e $+\gamma$)

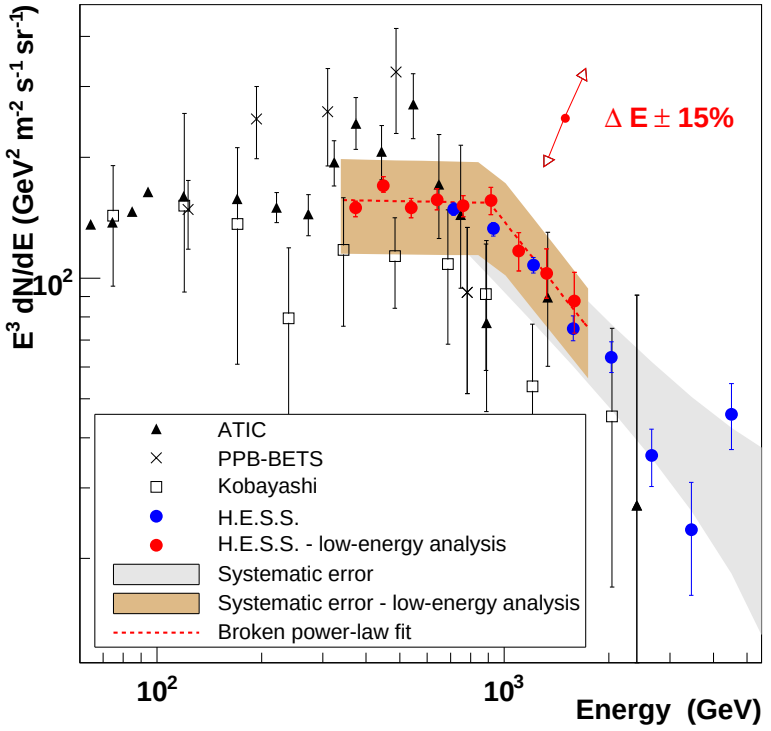
Nov 24, 2008

Sharp cutoff above $\sim$ 1 TeV

May 1, 2009

also at 300 and 800 GeV

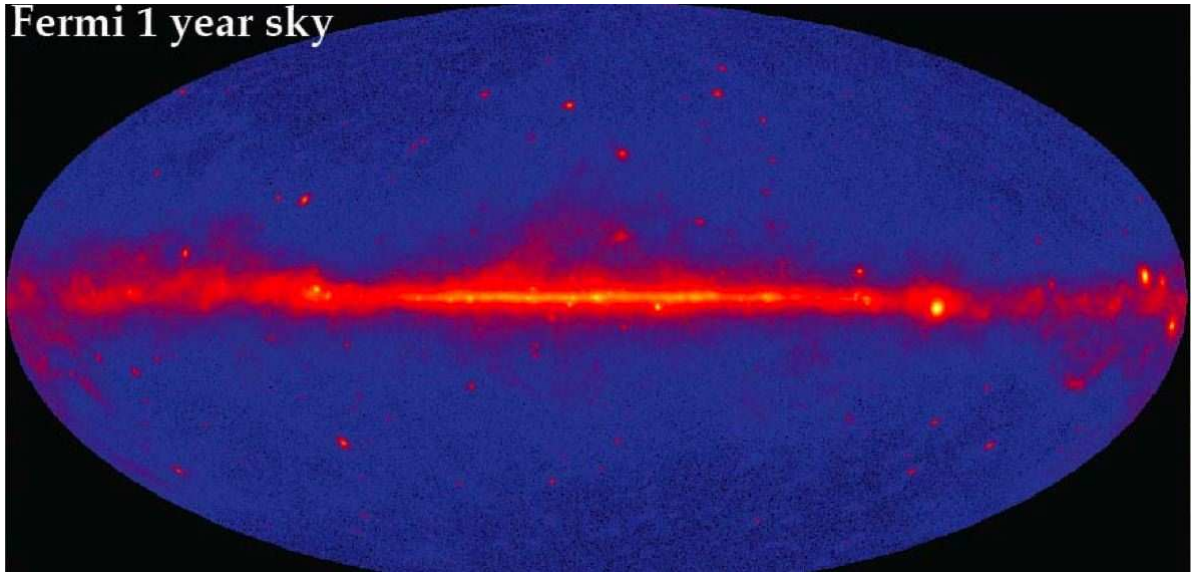




Fermi Space Telescope (FST)

(ex GLAST, γ-ray Large Area Space Telescope):

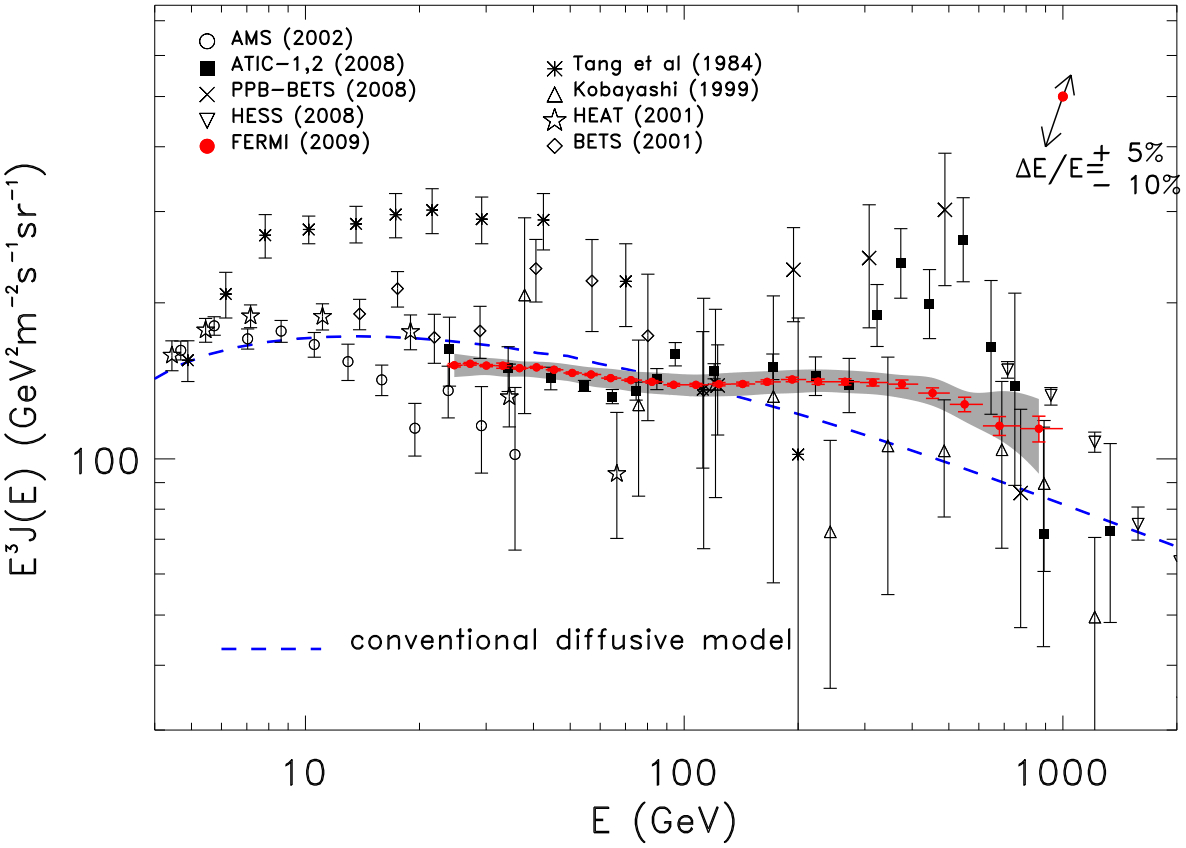
launched Jun 11,08 is providing γ ray spectroscopic data of unprecedented quality



FERMI): $e^+ + e^-$ spectrum 20 GeV to 1 TeV

FERMI -LAT
measured the spectrum
with better accuracy:
first $e^+ + e^-$ results
in the April APS Meeting
(May 4 2009)

Shows an excess over the conventional diffusive model of propagation GALPROP (in blue).

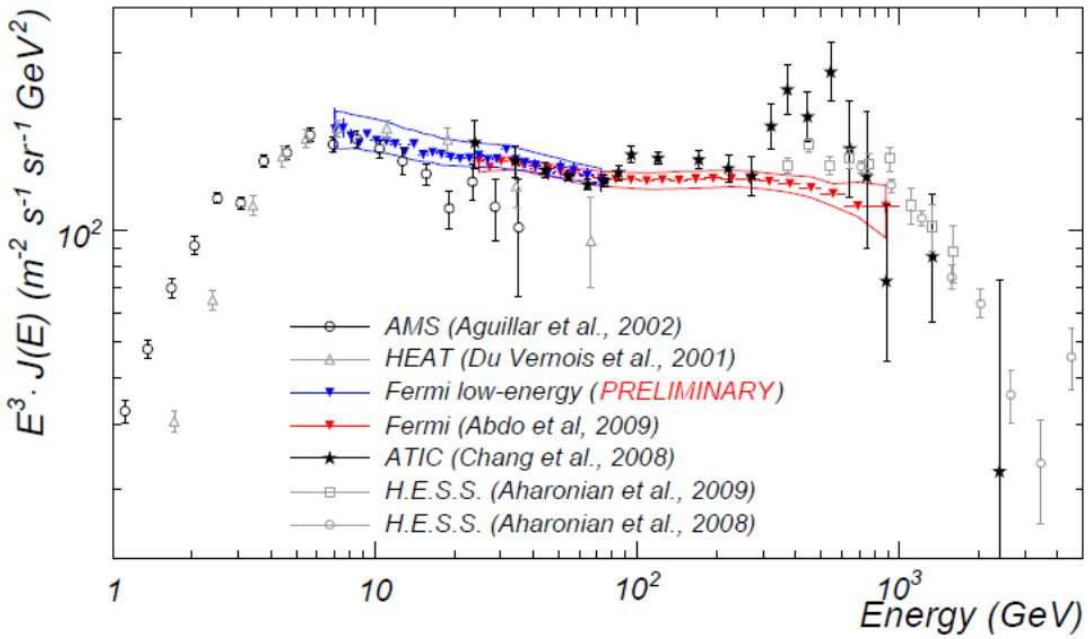


$$J_{e^\pm} = (175.40 \pm 6.09)\,\left(\frac{E}{1\ \mathrm{GeV}}\right)^{-(3.045\pm0.008)}\ \mathrm{GeV}^{-1}\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

FERMI: $e^+ + e^-$ spectrum

M. Pesce-Rollins, *2009 Fermi Symposium, Washington, D.C., Nov. 2-5*

GALPROP with modified parameters: does not fit the low-energy FERMI spectrum and does not fit the PAMELA ratio either



Sources?

- **e^+ e^- come from $<$ 1 kpc so must be produced locally**
  they rapidly loose energy through synchrotron and inverse Compton processes

- **what produces e^+ could produce $\bar{p}$ (PAMELA) and γ (FST-ACT's)!**

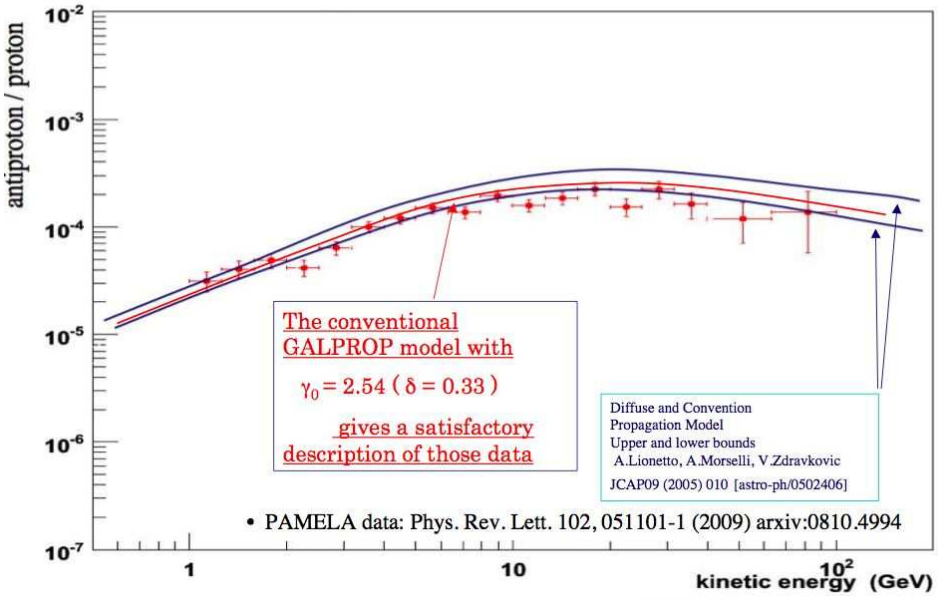
  - $\bar{p}$ come from a fraction of the galaxy, suffer convective mixing and spallation.

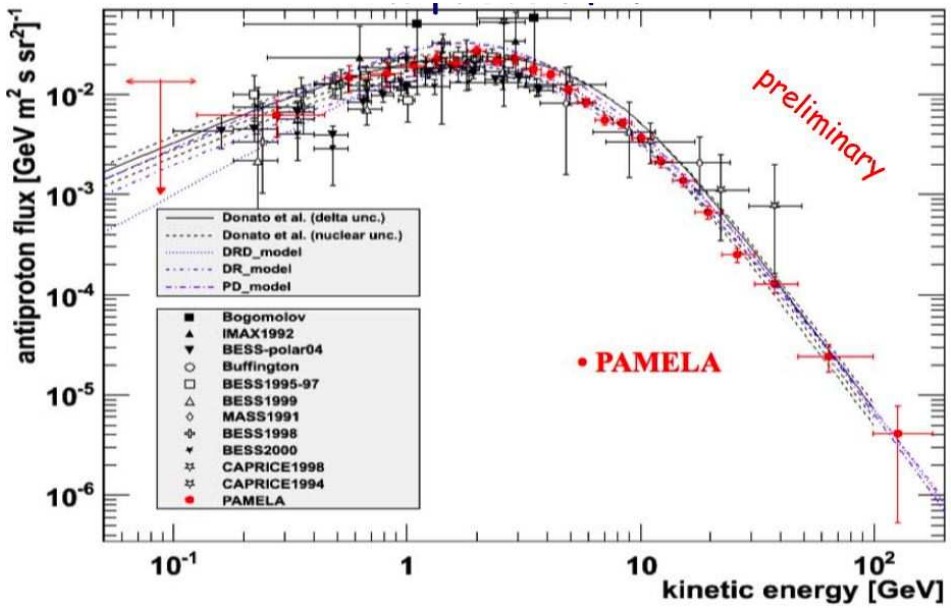
  - γ of E$<$ TeV come from cosmological distances (point to sources)

  But not signal has been seen in $\bar{p}$ or γ!

(Should keep in mind possible systematic error: rejection of p/e^+ 10^{-4} of PAMELA is barely enough to keep out contamination of p. AMS-2 will have 10^{-6})

PAMELA $\bar{p}/p$ and $\bar{p}$ results: (ratio Feb/08 and May/09 and flux preliminary)
are compatible with secondary cosmic rays





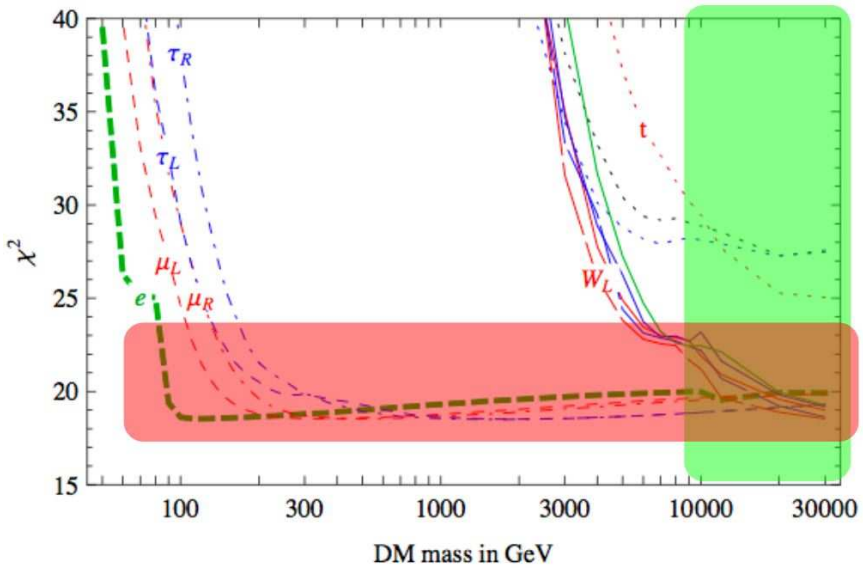
Sources: astrophysical? Dark matter? More than 500 papers!

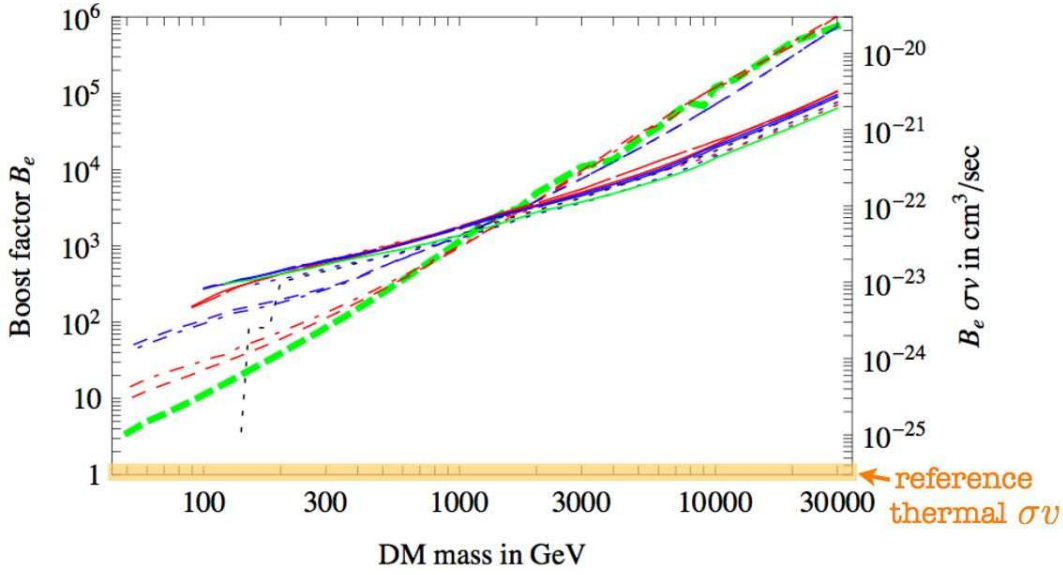
- Is a source of primary e^+ necessary?
  Secondary CR accelerated at the galactic sources (Blasi 09, Blasi & Serpico 09, Mertsch & Sarkar 09) But other secondary/primary ratios should rise too and they do not (Boron/Calcium by PAMELA)
- Known possible astrophysical sources?

  Pulsars (or other supernova remnants) nearby A good solution, although pulsars are not well understood (Aharonian, Atoyan and Volk, 95; Hooper, Blasi, Serpico 08; Yuksel, Kistler, Stanev 08; Profumo 08...)
- DM annihilation or decay?

  Thermally produced DM annihilation requires large enhancement of rate. Must produce almost exclusively leptons. Only contrived models survive all bounds (not your usual-straightforward-vanilla-flavor favorite model

"Thermal" DM annihilations: fit to e^+ and $\bar{p}$ PAMELA data with DM annihilating into single channels- BEFORE FERMI DATA (Figs from M. Cirelli)



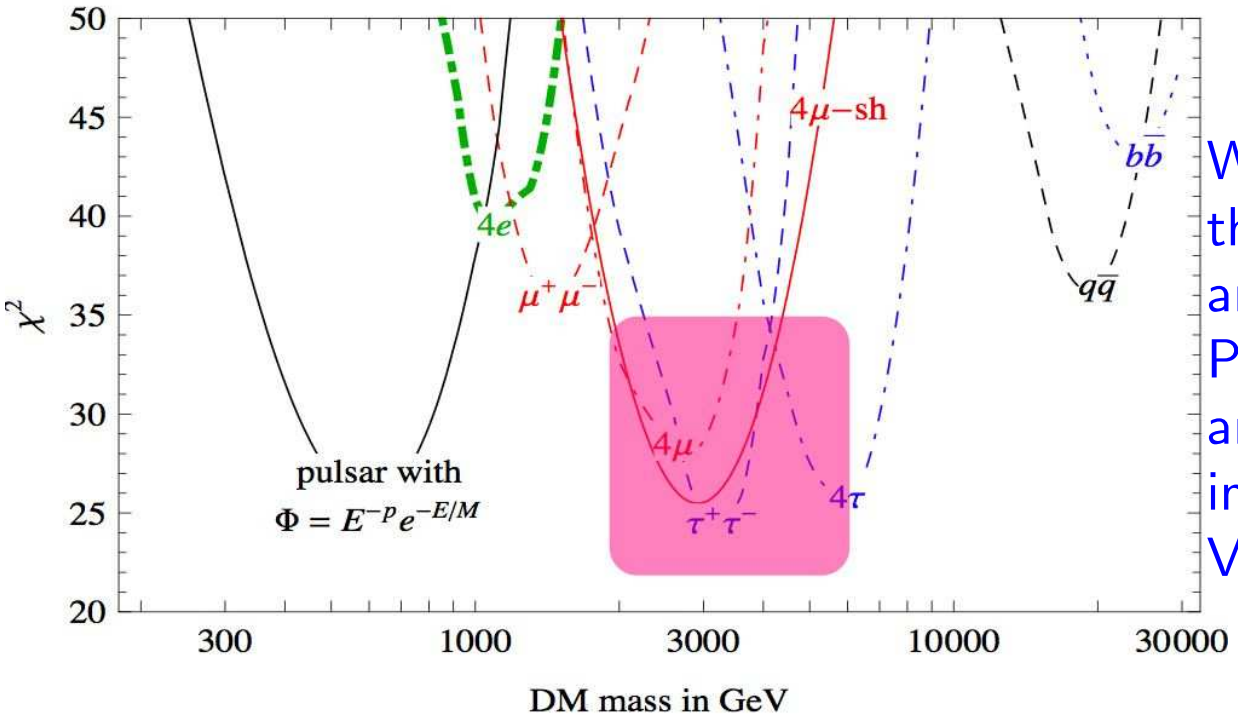


-Either annihilate into leptons, $B >$ few, or into W's for $m_\chi >$ TeV, $B > 10^2$

-Cross sections needed are $\sigma_{annih} \simeq$10 to $10^3 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$ or $B \simeq$10 to 10^3

"Thermal" DM annihilation adding FERMI and HESS

(Meade, Papucci, Strumia, Volansky, 0905.0480) (Figs from M. Cirelli)



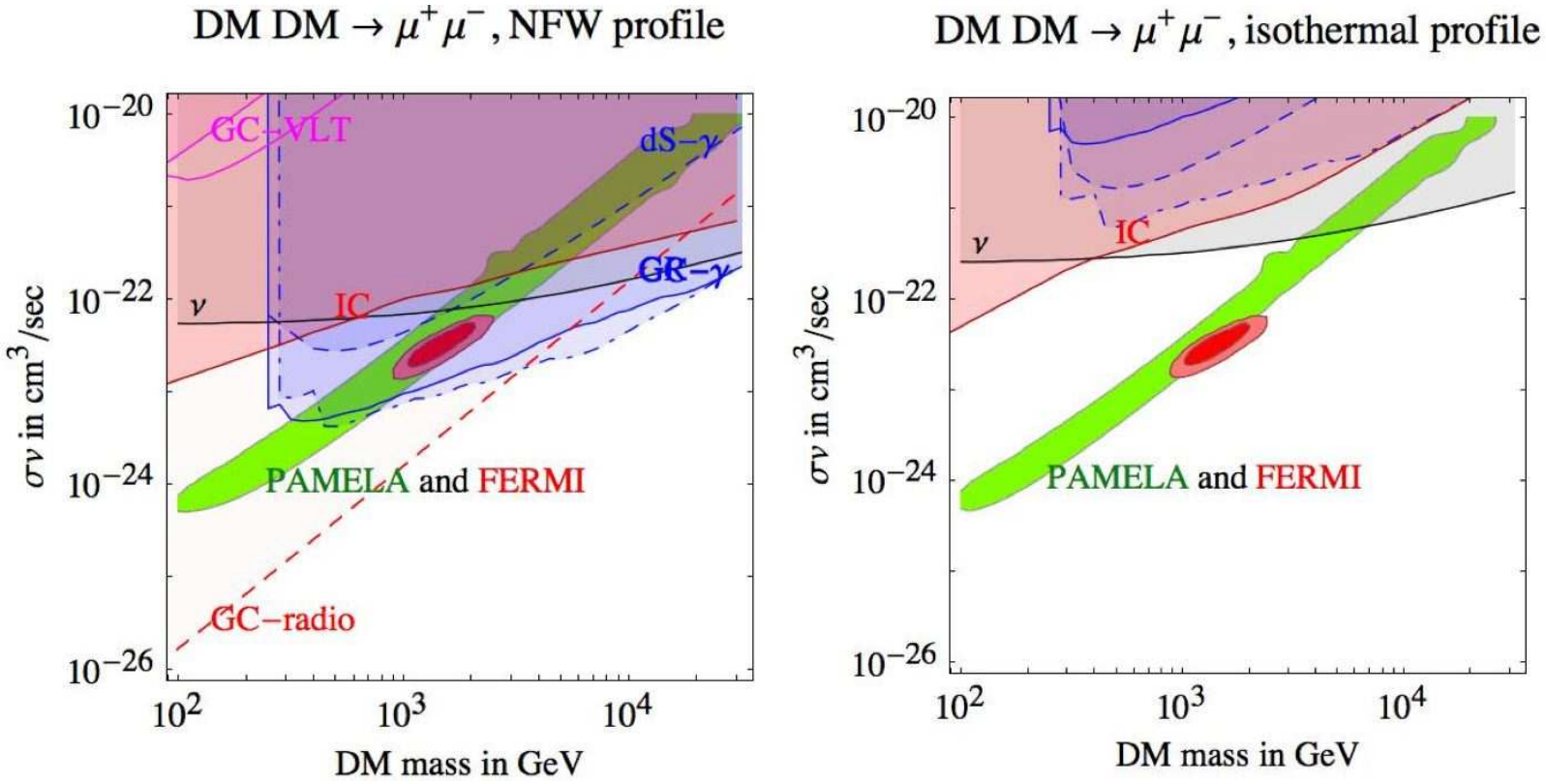
WW and e^+e^- do not fit the data well any longer and only $m > 1$ TeV OK. Preferred model: DM annihilates mostly into $\tau^+\tau^-$ or 4μ or 4τ VERY UNNATURAL!

Still, other constraints besides PAMELA, FST and HESS $e^+ + e^-$ data:

- γ from DM annihilation in the Galactic Center (HESS has measure γ emission form the GC and the Galactic Ridge)
- Radio waves from synchrotron radiation of $e\pm$ (from DM annihilation) in the GC
- γ from DM annihilation in the Sg Dwarf galaxy
- EGRET and Fermi diffuseγ emission set bounds on Inverse Compton of $e\pm$ (from annhilations) on the CMB, IR and starlight γ (probes regions outside the GC)
- ν from the GC (from SuperKamiokande)

Constraints from the GC require Isothermal Core!

(so astrophysical $B = 1$) (Meade, Papucci, Strumia, Volansky, 0905.0480)



Large enough local DM annihilation signal (0.1 to 1 kpc^3):

- $\sigma_{\rm annh}$ is large also in the early Universe and the pre BBN era is non standard , e.g. a Wino Kane, Lu and Watson 09

- The enhancement is astrophysical

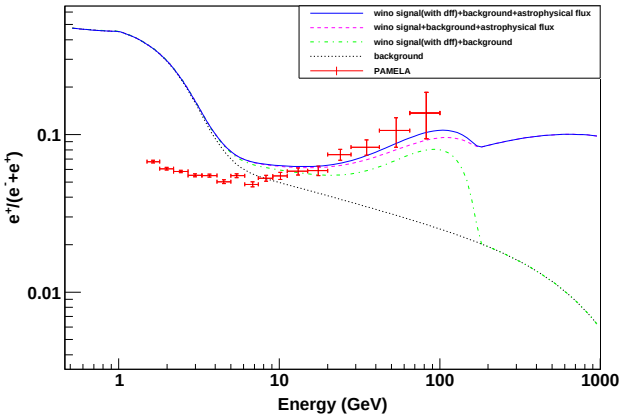
- $\sigma_{\rm annhilation}$ is enhanced in the halo (small v) with respect to that in the early Universe (larger v)

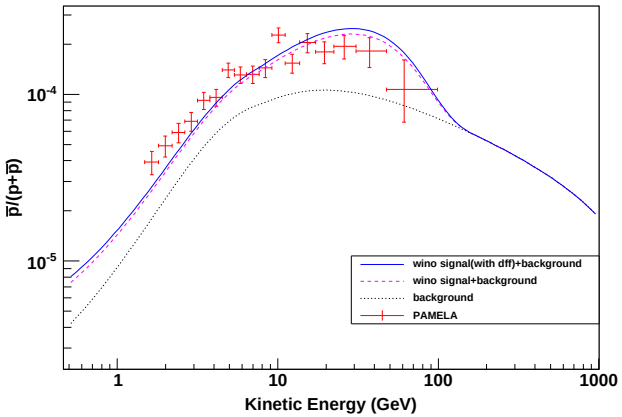
- Better if DM annihilates mostly into leptons
  (Leptonic Higgs Hall, Kumar 09, leptophilic DM Fox & Poppitz 09,
  XDM models with a low mass scalar Arkani-Hamed, Finkbeiner, Slatyer, Weiner 09

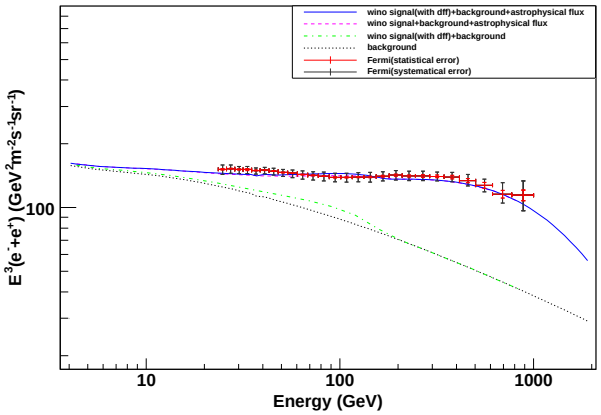
"Non-Thermal" annihilating DM:

May be WIMP has a large $\sigma_{\rm annhilation}$ and is non-thermally produced in the early universe (non-standard pre-BBN cosmology) e.g. a Wino (Kane, Lu and Watson 09)

It does not need any boost! Fit to e^+ PAMELA data is OK
but fit to Fermi data requires "conspiracy" with astrophysical source!







Still awaiting the results of $\bar{p}$ in this model- need to incorporate it in GALPROP

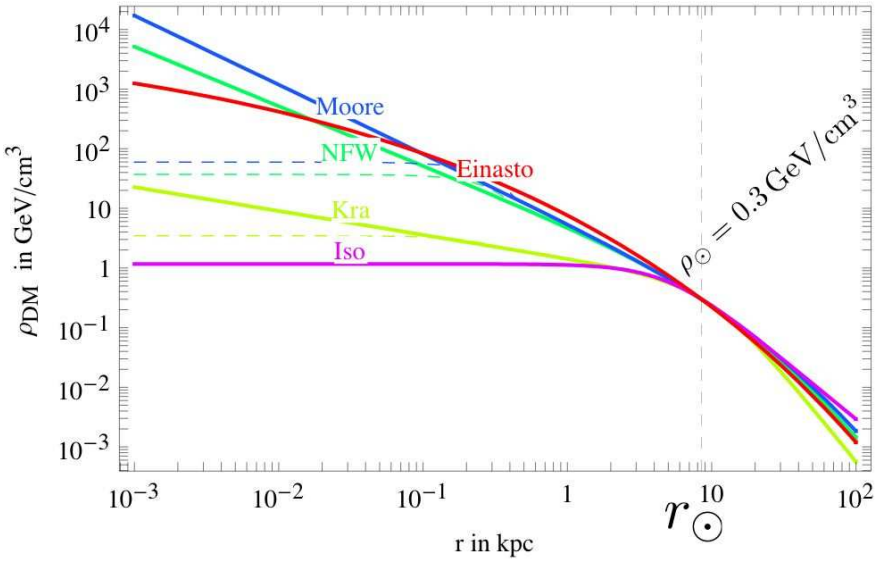
Astrophysical boost factors: B is very different for γ, $e+$ and $\bar{p}$!!!

-Could have one DM clump nearby (but probability is 10^{-4} !)

VIRGO and Via Lactea II: clumps are more effectively destroyed near the GC

-Just due to the smooth component, B depend on E+Halo Model: Bmax.$\simeq$10 B can be ~ 10 for cusped halo models but ~ 1 for cored models.

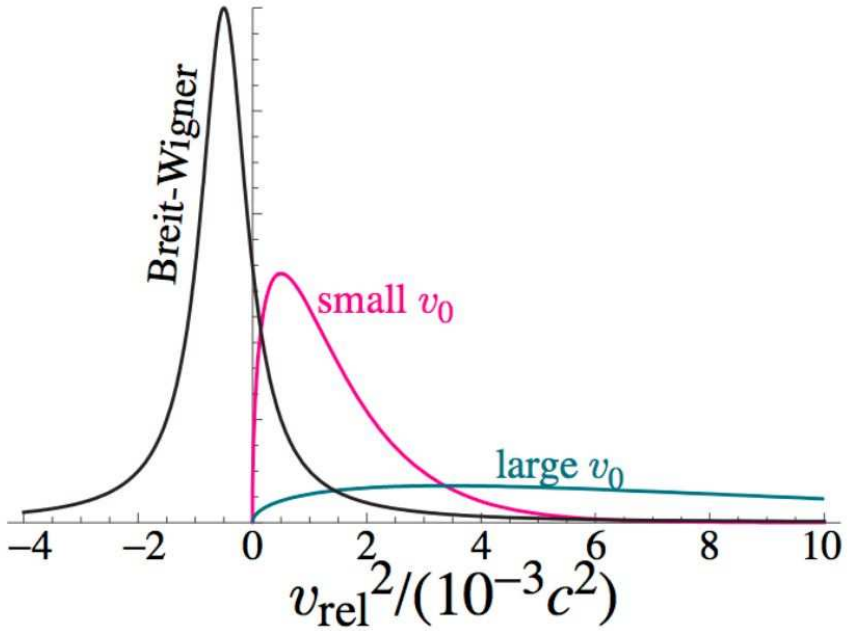
(e.g. Lavalle, Yuan, Maurin & Bi, A&A 429, 427, 08)



Particle boost-factors:

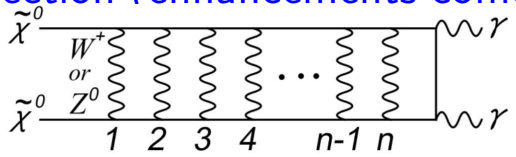
May be the $\sigma_{\rm annhilation}$ is enhanced with respect to that in the early Universe

- Resonance enhancement: DM annihilation cross section has a narrow resonance just below threshold (Cirelli et al 08; Nath et al. 08; Ibe, Murayama &Yanagida 08)



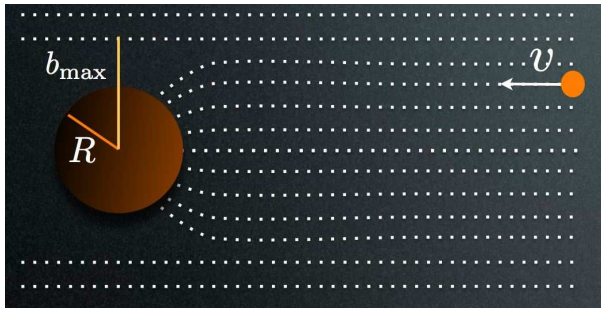
Particle boost-factors:

- **"Sommerfeld resonance"**: long distance attractive forces modify the wave function of the DM particles which enhances the annihilation cross section (enhancements come from ladder diagrams in perturbative expansion) (Iengo 08)



  - Works for heavy neutralino-chargino almost degenerate; attrative Yukawa force from multiple t-channel W and Z exchange, forms bounds states at small (galactic) velocities (no effect in the Early Universe) (Hisano, Matsumoto and Nojiri, 03; Hisano, Matsumoto and Saito 04)
  - or Yukawa potential due to the exchange of a light hidden gauge or scalar boson ϕ (Arkani-Hamed, Finkbeiner, Slatyer, Weiner 09)

    Classical analogy: in the presence of a long range attractive force (like gravity)
    $\sigma = \sigma_0(1 + v_{escape}^2/v^2) > \sigma_0 = \pi R^2$
    thus for $v << v_{escape}$, $\sigma >> \sigma_0$



Particle models:

- Annihilating DM models with minimal extensions of the SM: heavy WIMPs e.g. Inert Doublet Model Tytgat et al 0901.2556

- Annihilating DM models with considerable extension of the SM: complex dark and hidden sector e.g. Pospelov et al 07, Arkani-Hamed et al 08, Nomura % Thaler 08, Baai & Han 08, Cirelli etal 08, Fox & Poppitz 08, Park &Shu 09, Phalen, Pierce & Weiner 09...

  - $\sim$TeV mass DM,
  - new attractive forces mediated by light $\sim$ GeV bosons (attractive forces to produce the Sommerfeld enhancement)
  - leptophilic either
    -because the DM carries Lepton number
    -or because of kinematics (light mediator).

- Decaying DM Ibarra et al 07 to 09, Nardi, Sannino & Strumia 0811.4153; Arvanitaki et al 0812.

"A Theory of DM": Arkani-Hamed, Weiner, Finkbeiner... 08

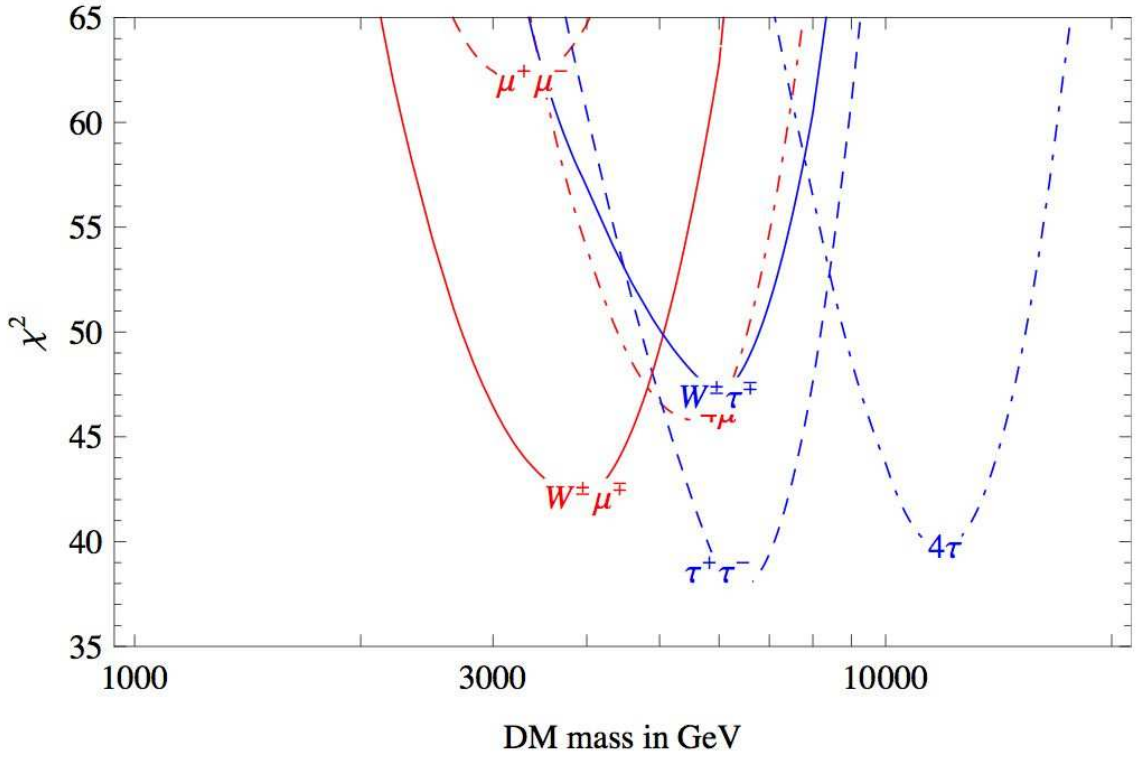
- χ is a 500-800 GeV mass WIMP
- ϕ few GeV new gauge boson ("dark photon") coupled only to DM with typical strength mediates new attractive forces which produce the Sommerfeld enhancement and is "leptophilic" because it is so light that can only decay into e^+e^- or $\mu^+\mu^-$ (not τ's-done before FERMI !)
- To account for DAMA and INTEGRAL,
  χ is a multiplet of states and ϕ is a non- Abelian gauge boson of a group G_{dark}
  (the mass splittings are due to loops of ϕ bosons)
  -inelastic scatterings (IDM) explain DAMA $\delta m \simeq 100$ keV
  -excited-DM (XDM) explain INTEGRAL $\chi\chi \to \chi\chi^*$ and $\chi^* \to e^+e^-$ $\delta m \simeq 1$ MeV
- Major additions to SUSY signals depend on realization: GeV-dark Higgses and gauge bosons decay into visible particles, dominantly lepton "jets", MSSM LSP decays into the true "dark" LSP, thus many lepton jets with GeV invariant masses expected...Arkani-Hamed, Weiner 0810.0714 [hep-ph]

Many variations: Some are...

- Secluded DM (precursor model to the others) Pospelov, Ritz et al 0711.4866, Nath et al 0810,5762
- Axion Portal: ϕ is a pseudoscalar axion-like Nomura, Thaler 08
- singlet-extended UED: χ is KK right handed neutrino, ϕ is an extra bulk singlet Bai, Han 08
- χ carrries Lepton number $L_\mu - L_\tau$ Cirelli et al 08, Fox, Poppitz 08
- χ annihilates into another particle that carries Lepton number and decays weakly Phalen, Pierce Weiner 09
- ...

Decaying DM: (With $\tau > t_U \simeq 10^{17}$ s)

PAMELA+FST+HESS require: multi-TeV mass, $\tau > 10^{26}$ s, decays mostly into 2nd or 3rd generation leptons ($\chi \to W\ell$, $\bar{\ell}\ell\nu$, 4μ) Very tuned models!



Meade et al. 0905.0480

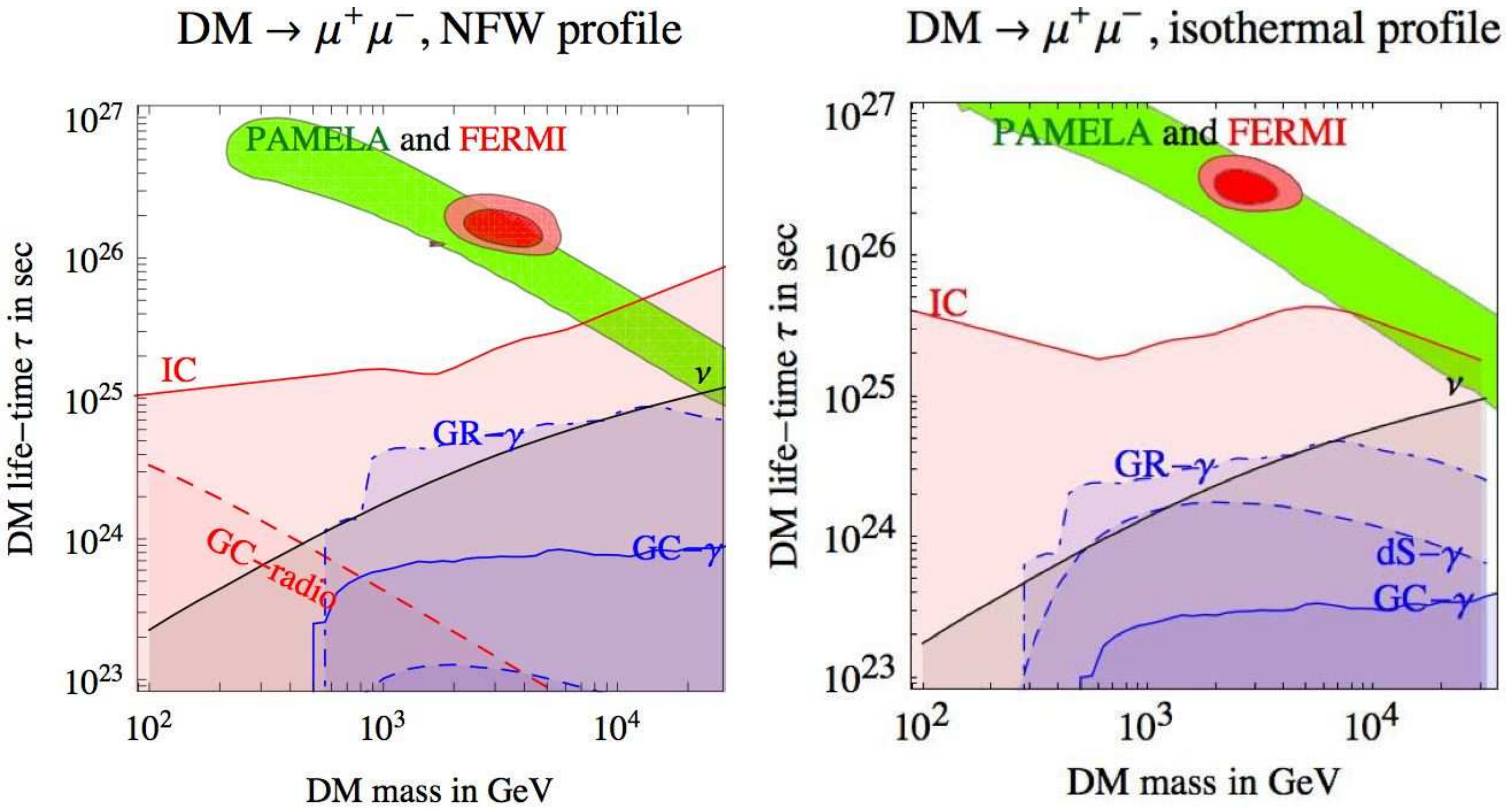
Decaying DM:

Ibarra et al 07 to 09, Nardi, Sannino & Strumia 0811.4153; Arvanitaki et al 0812.

Candidates for multi TeV mass DM decaying with $\tau > 10^{26}$ s

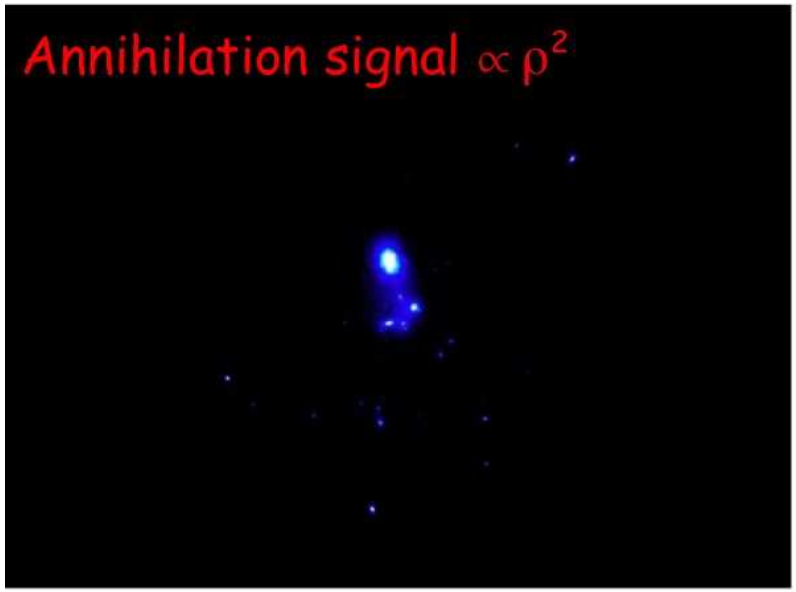
- SuperWIMPs,
- gravitinos with broken R-parity,
- right- sneutrinos in models with Dirac neutrino masses,
- hidden sector gauge bosons or gauginos,
- hidden sector fermions etc...

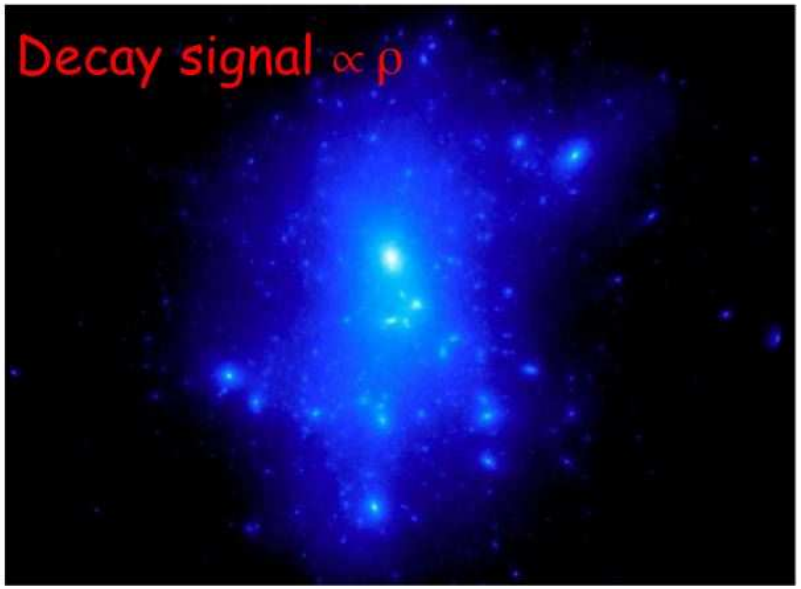
Decaying DM: any halo profile is OK PAMELA, FST, HESS and additional constraints due to $\bar{p}$, γ-rays, ν, antideuterium- any halo profile is OK) Example:(Meade, Papucci, Strumia, Volansky, 0905.0480)



How to distinguish decaying from annihilating DM?

Gamma-ray observations will be crucial (Fig. from B. Moore)





SUMMARY

Direct Detection: Models to make all data compatible are difficult to produce and testable with more data (IDM, light WIMPs, DM interacting with e...). New hints from CoGeNT and maybe CRESST for light WIMPs?

Indirect Detection: Plenty of data coming in FERMI, PAMELA, AMS-2, ACTs:

ATIC $e^+ + e^-$ data: rejected Fermi and HESS. FERMI finds another excess.

PAMELA and FERMI data can be explained by nearby pulsars (requires large efficiency to produce $e\pm$, 10 to 30% or many more near pulsars $<$ 3 kpc, which is very likely)

If it is Annihilating DM: not the simplest DM scenarios (goes preferentially into leptons of 2nd and 3rd generation, has large annihilation rate so either non-thermal or some boost factor B, has $\sim$TeV mass and disfavors cusped halo profiles)

If it is Decaying DM, must decay mostly into leptons of the 2nd or 3rd generation, multi-TeV mass with $\tau \sim 10^{-26}$ s (very suppressed!)

We need more data

CONCLUSIONS-OUTLOOK

DM searches are independent and complementary to collider searches in multiple ways... and they are advancing fast...
Lots of data lead to many hints... data driven recent burst of model building due to difficulty in accommodating all hints...

So far, no firm DM signature found but models opened our imagination and expectations for things to come... the physics of DM and the physics needed at the EW scale may be different...

In most scenarios one can think of the LHC should find at least a hint of the new physics...
Besides, DM may have several components to be found in different ways...

DM particles would be our first probe of the immediate pre-BBN cosmology

All possibilities are still open.... hopefully not for long!