Dark Forces
Workshop Report

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Jlab Theory Cake Seminar

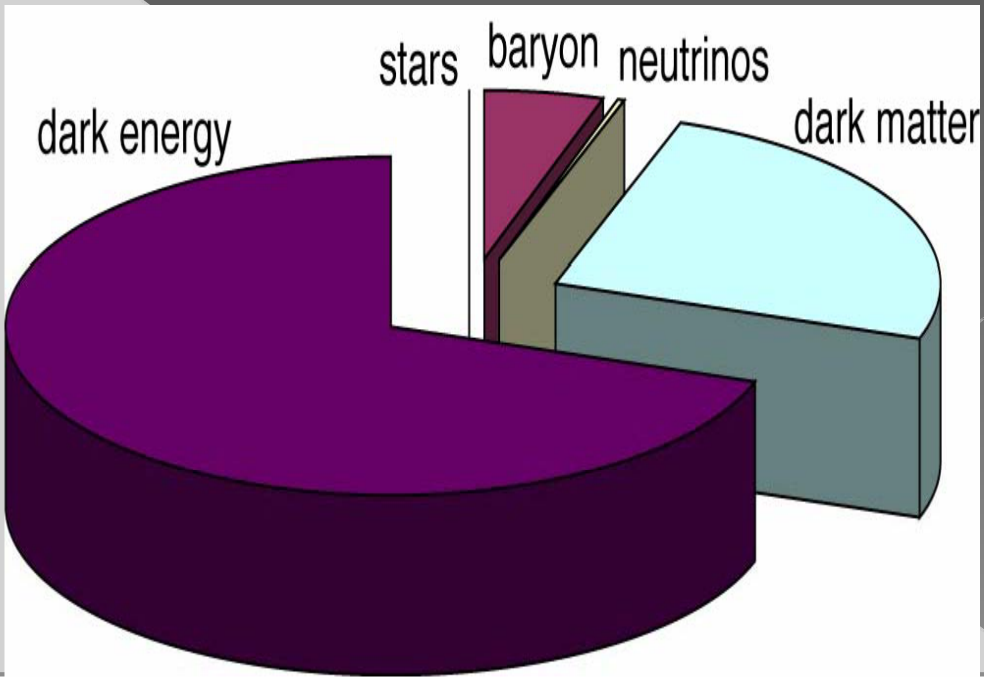
November 3, 2009

Plan of Talk

- Introduction to a Dark Matter problem
- New data and their interpretation
  - Implications for new particles at MeV-Gev scale and accelerator-based searches
  - Info from the "Dark Forces" Workshop, SLAC, Sept.'09

Matter/Energy Budget of Universe

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.3–10%
- Rest of ordinary matter (electrons and protons) are ~5%
- Dark Matter ~30%
- Dark Energy ~65%
- Anti-Matter 0%

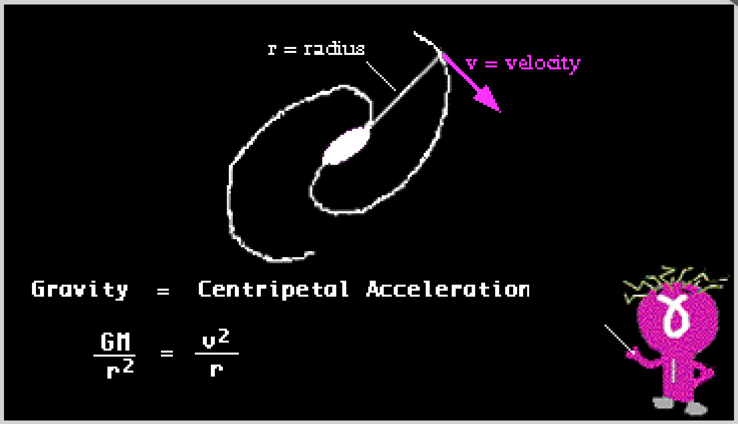


Dark Matter: Observational Evidence

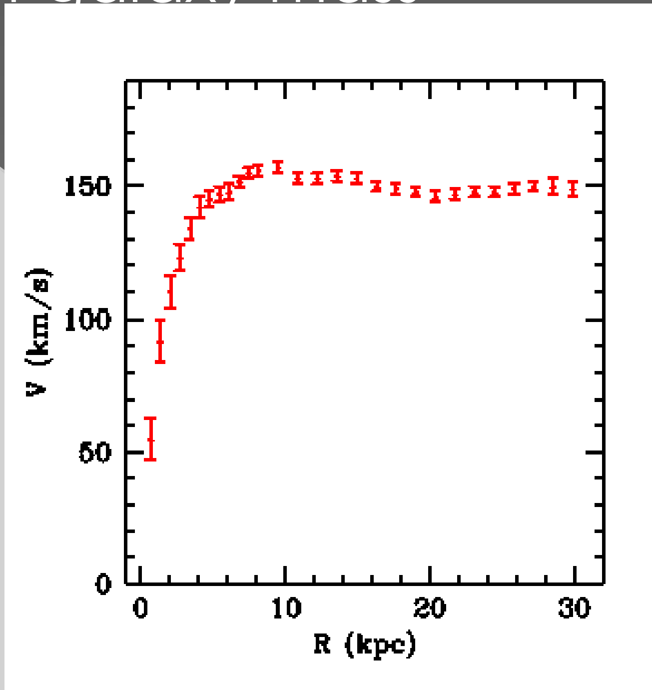
- Fritz Zwicky (1933): Dispersion speed of galaxies in a Coma Cluster too high => `dynamic mass' is ~400 times larger than `luminous mass'
- S. Smith (1936): similar observation in Virgo Cluster; x200 excess in mass, can be explained by presence of additional matter between the galaxies

Galactic rotation

- Vera Rubin (1970): Measured rotation of spiral galaxies, discovered stars on the periphery revolve too fast around the galaxy center=> an invisible halo carries ~90% of galaxy mass



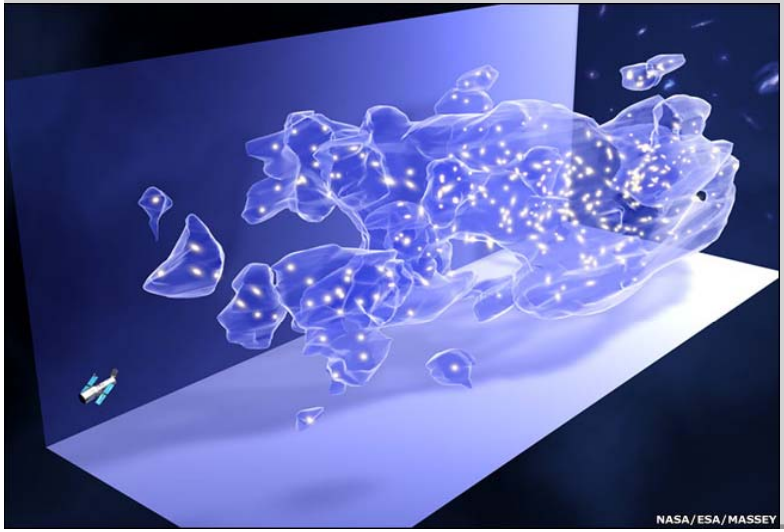
$v \sim R^{-1/2}$?

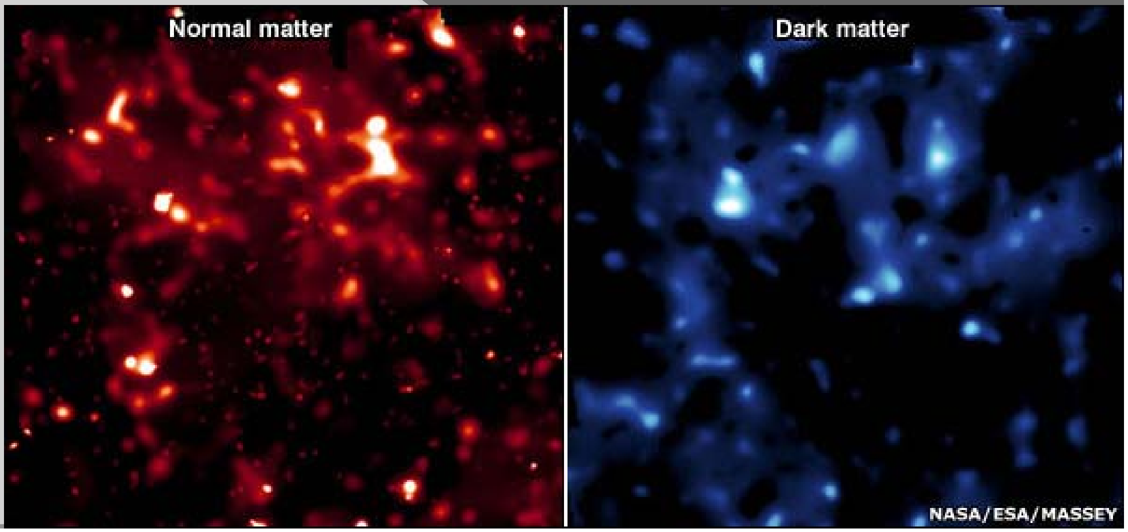


Gravitational lensing: 3D map of observable Universe from Hubble telescope

R. Massey et al, Nature 445, 286 (2007):
Dark Matter Maps Reveal Cosmic Scaffolding

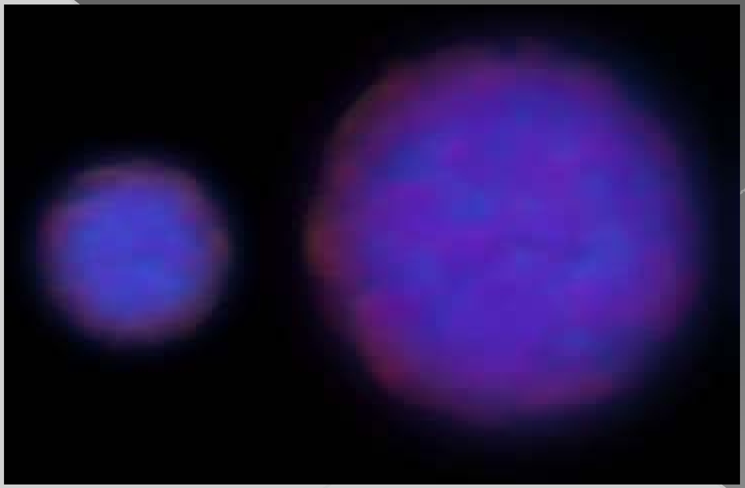
- Area of 1.6 deg^2
- ~1/2 million galaxies





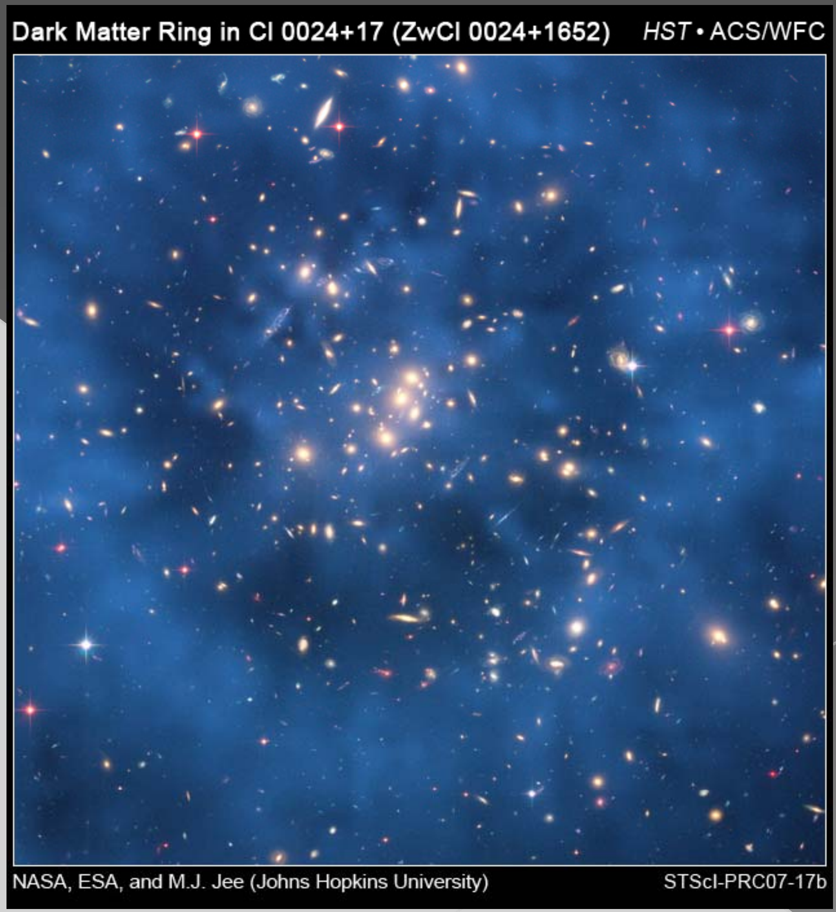
Chandra X-ray observatory data’06 (see chandra.harward.edu)

- Galaxy cluster 1E 0657-56 (`bullet cluster’)
- Dark matter (blue) not slowed by the impact; while hot gas (red) is slowed/distorted by drag force
- Separation during collision



More dark matter evidence (2007)

- Ring of dark matter formed in collision of two galaxy clusters



What is Dark Matter?

- An unknown elementary particle that only weakly interacts with ordinary matter
  - May be light ($\sim 10^{-3}$ eV) "axion" (or axion-like particle, ALP)
  - May be heavy ($\sim 10^{6}$ eV) "WIMP"
    - Evidence reported April'08 by DAMA Collab., observed semi-annual variations of electromagnetic background in NaI detector

http://neutrino.pd.infn.it/NO-VE2008/prog-NOVE.htm

Dark Forces Workshop
Searches for New Forces at the GeV-scale
SLAC, September 24th to 26th, 2009

Theoretical models related to dark matter have proposed that there are long-range forces mediated by new gauge bosons with masses in the MeV to GeV range and very weak coupling to ordinary matter. The experimental constraints on the existence of these new gauge bosons are quite weak. This workshop will bring together theorists and experimentalists to stimulate progress in searching for these "dark forces" in three arenas:

- New fixed-target experiments at electron and proton accelerators such as JLab, SLAC, and Fermilab;
- Searches at high-luminosity e+e- experiments, including BaBar, BELLE, CLEO-c, KLOE, and BES-III;
- Searches at the Tevatron experiments

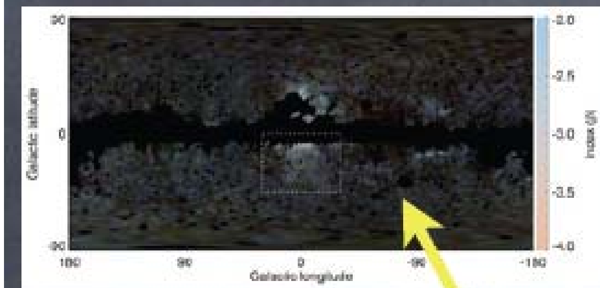
Talks available at http://www-conf.slac.stanford.edu/darkforces2009/

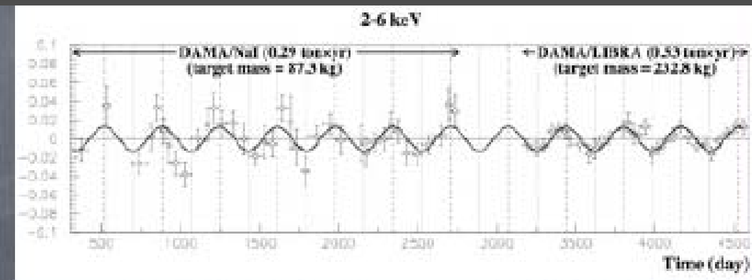
Era of Data

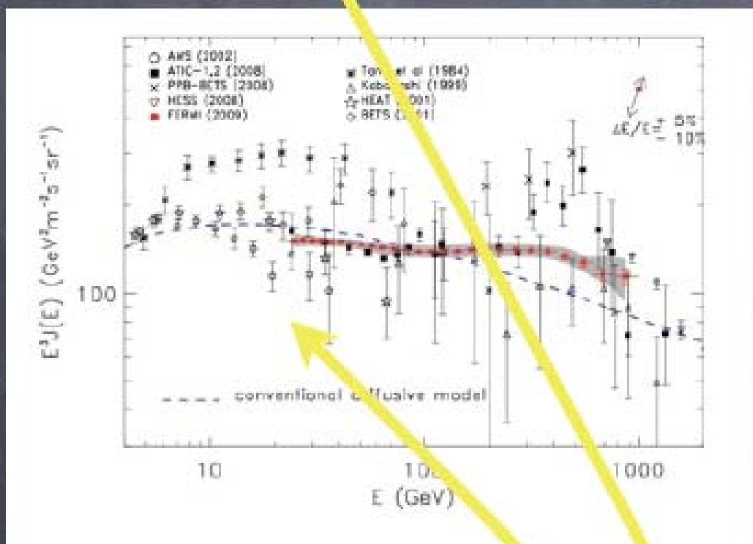
I will follow arguments of several speakers of SLAC Dark Forces Workshop (2009) on Dark-Matter interpretation of recently observed astrophysics anomalies

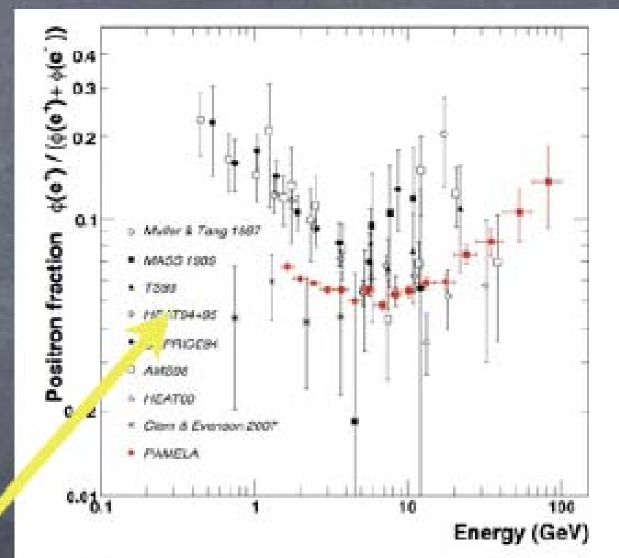
- Cosmics: PAMELA, Fermi, ATIC, HESS, AMS, ACTs, WMAP, Planck...
- Direct: CDMS, DMTPC, XENON, LUX, CRESST, COUPP, PICASSO, KIMS...
- Production: LHC/Tevatron, **Fixed Target, Beam dump**

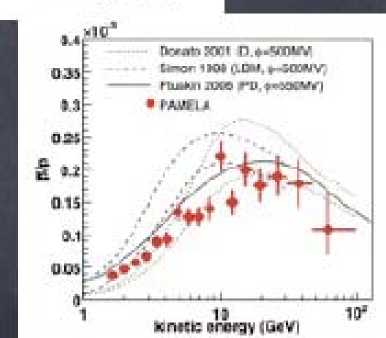
Era of Anomalies







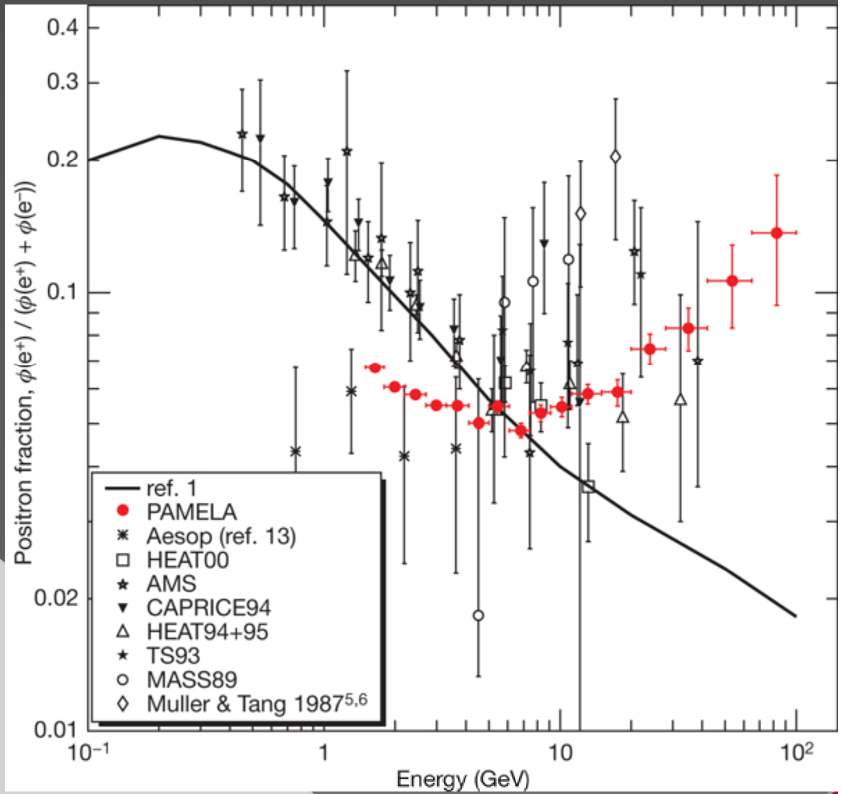




Indications of high energy electron or positron production

PAMELA positron fraction with other experimental data and with secondary production model

PAMELA
The Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics has reported results indicating a sharp upturn in the positron fraction (e+/(e+ + e−)) from 10 − 100GeV, counter to what is expected from high-energy cosmic rays interacting with the interstellar medium (ISM).
This result confirms excesses seen in previous experiments, such as HEAT and AMS-01. One possible explanation for this is dark matter annihilation into e+e−
`Sommerfeld enhancement 'essential

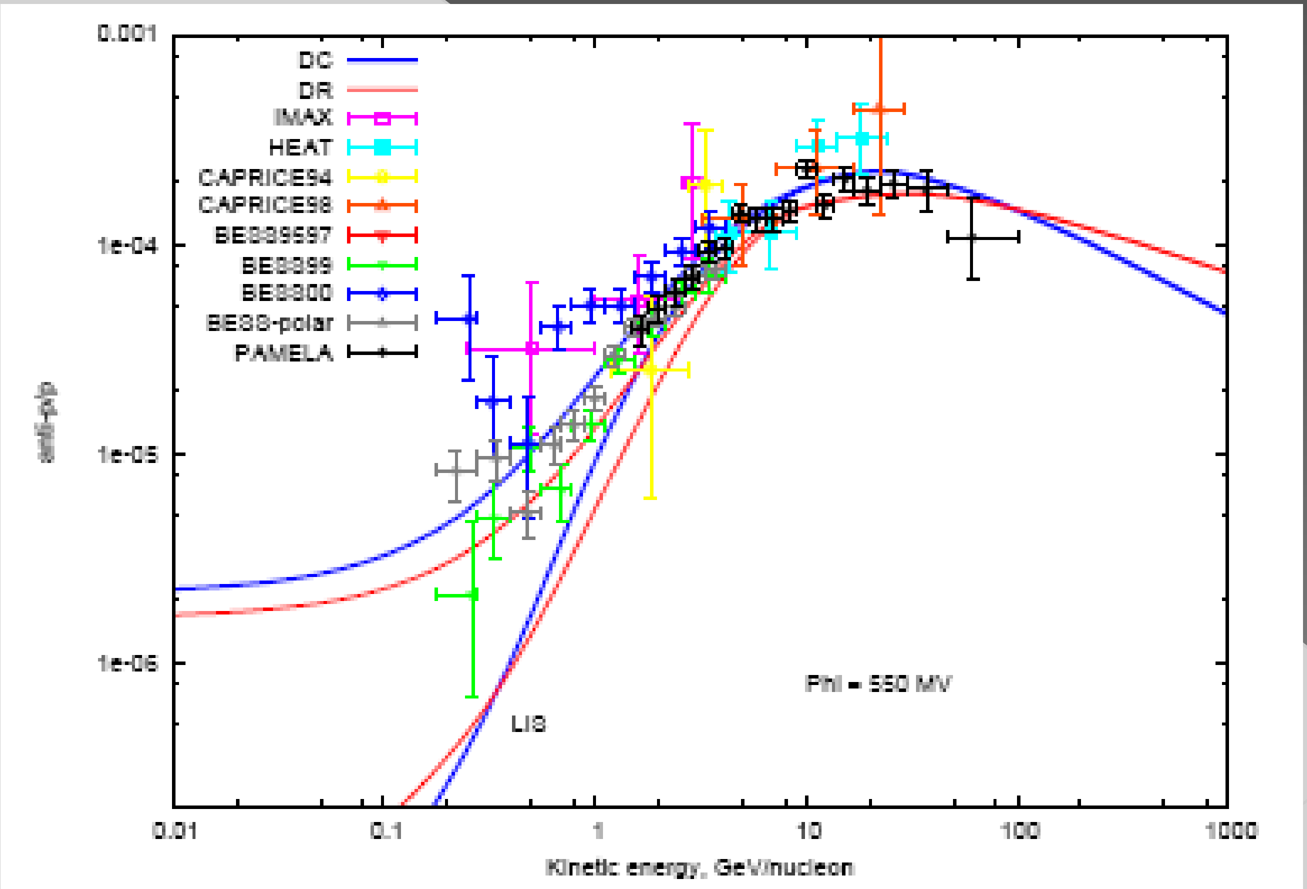


Standard-Model explanation: Pulsars (Hooper et al, JCAP01 (2009)025

O Adriani *et al. Nature* **458**, 607-609 (2009) doi:10.1038/nature07942

PAMELA an antiprotons

- No excess in the antiproton flux

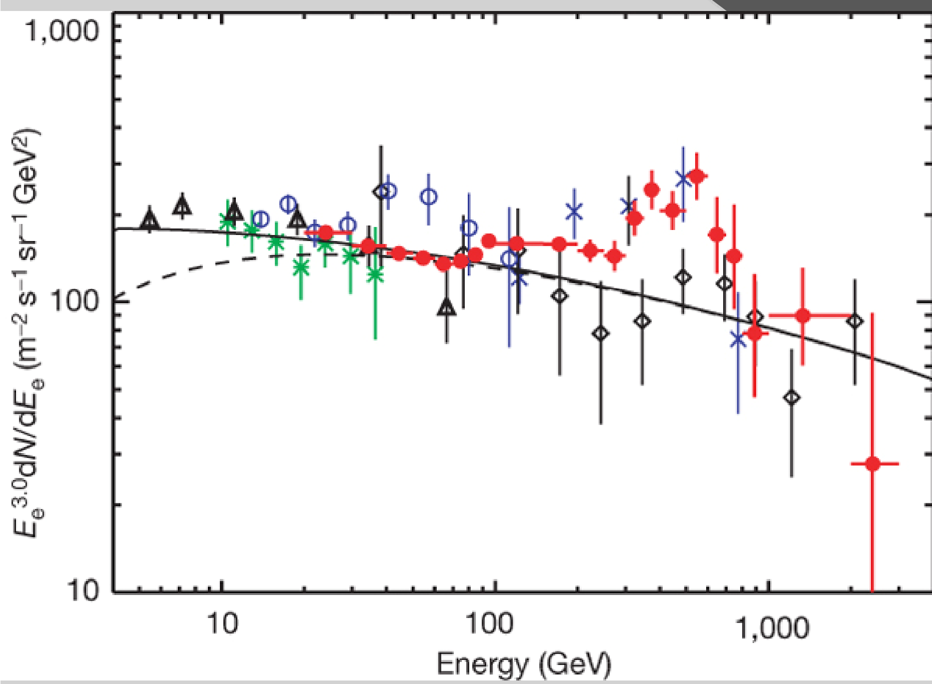


ATIC

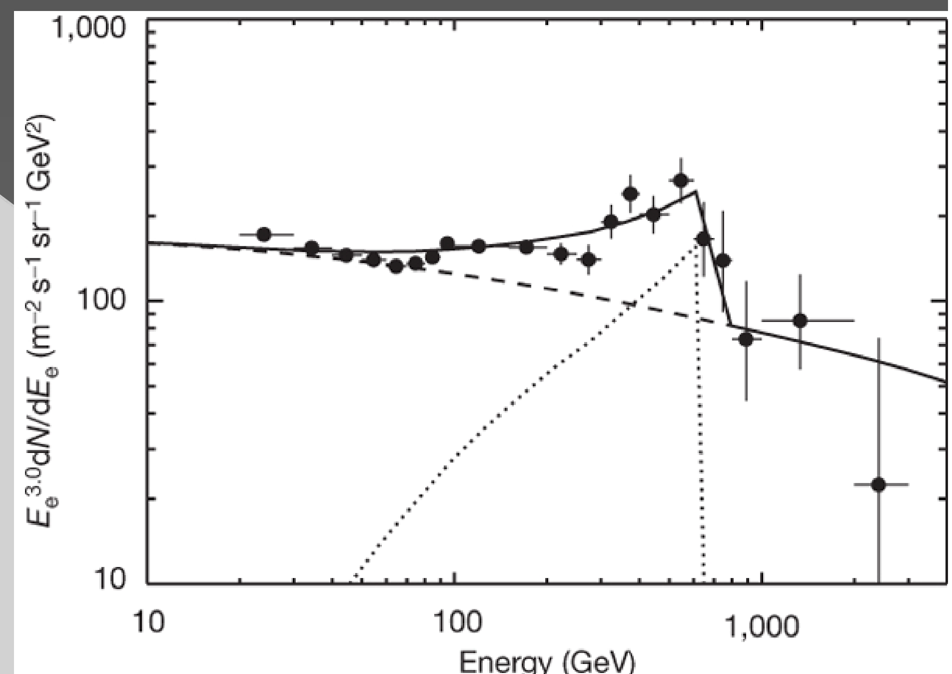
- **An excess of cosmic ray electrons at energies of 300.800 GeV.** [J. Chang *et al.*] **Nature 456:362-365, 2008**.
- The Advanced Thin Ionization Calorimeter is a balloon-borne cosmic ray detector which studies electrons and positrons (as well as other cosmic rays) up to ~ TeV energies, but cannot distinguish positrons and electrons. The primary astrophysical sources of high-energy electrons are expected to be supernovae: electrons are accelerated to relativistic speeds in supernova remnants and then diffuse outward. The ATIC-2 experiment reported a $4-6\sigma$ excess (over a simple power law) in its $e^+ + e^-$ data at energies of ~ 300− 800GeV, with a sharp cutoff in the 600 − 800GeV range.
- Dark matter would seem a natural candidate for this as well, with its mass scale determining the cutoff.

ATIC anomaly

ATIC results showing agreement with previous data at lower energy and with the imaging calorimeter PPB-BETS at higher energy.



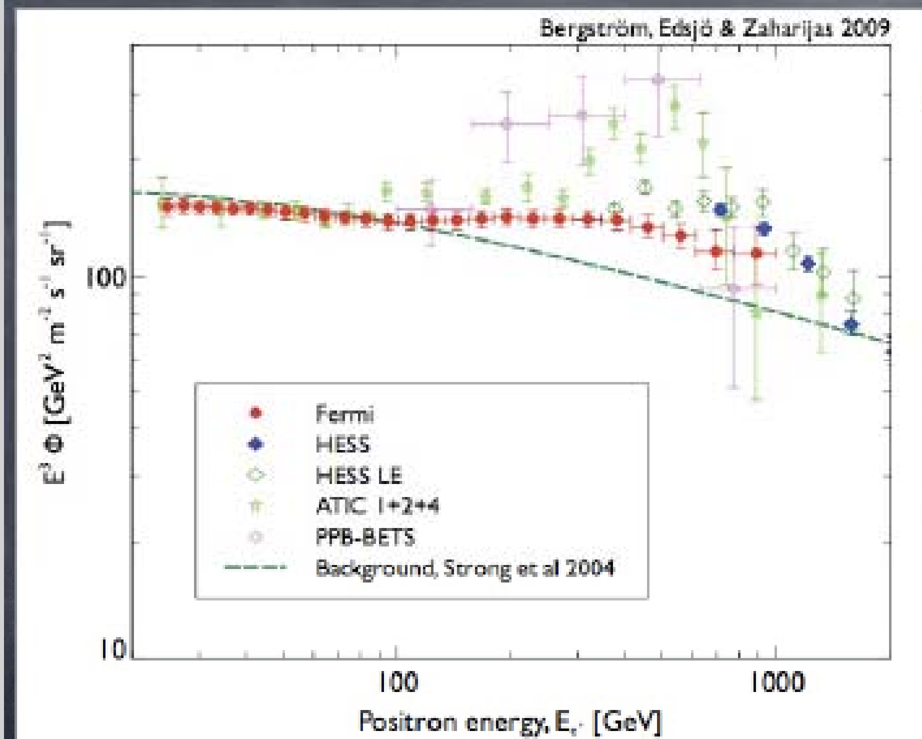
Assuming an annihilation signature of Kaluza–Klein dark matter, all the data can be reproduced.

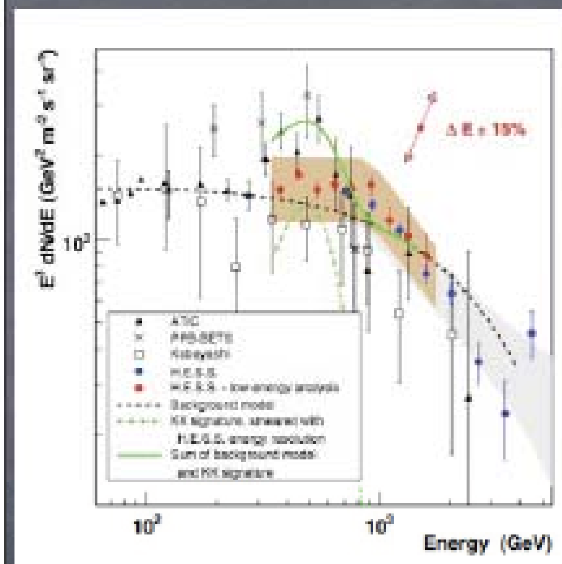


J Chang *et al. Nature* **456**, 362-365 (2008) doi:10.1038/nature07477

Data on electons+positrons combined

Fermi, HESS, ATIC, PPB-BETS



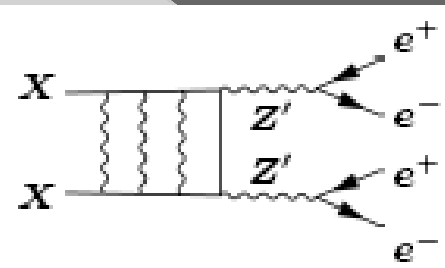


- **Harder** spectrum than expected - no break until ~ TeV

Sommerfeld enhancement

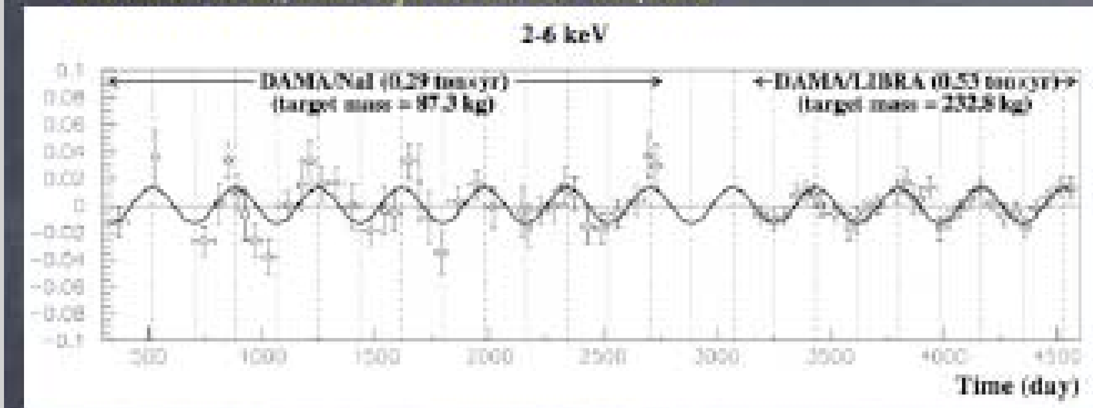
- A heavy DM particle X (100s GeV) could annihilate into GeV Z', which would decay preferentially into light SM particles because of its small mass. The necessary large enhancement in the XX annihilation cross section (needed in all such models) could be accounted for by the Sommerfeld enhancement (from the distortion of the wave functions at low energy), due to repeated Z' exchange

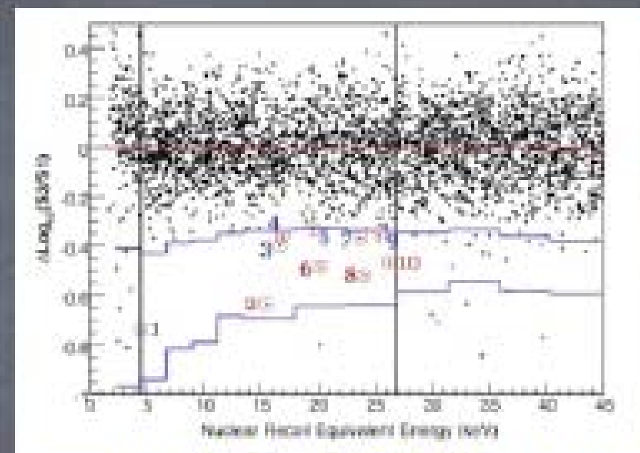
$$XX \to Z'Z' \to \text{light SM}$$



DAMA experiment

Bernabei et al., Eur.Phys.J.C56:333-355,2008

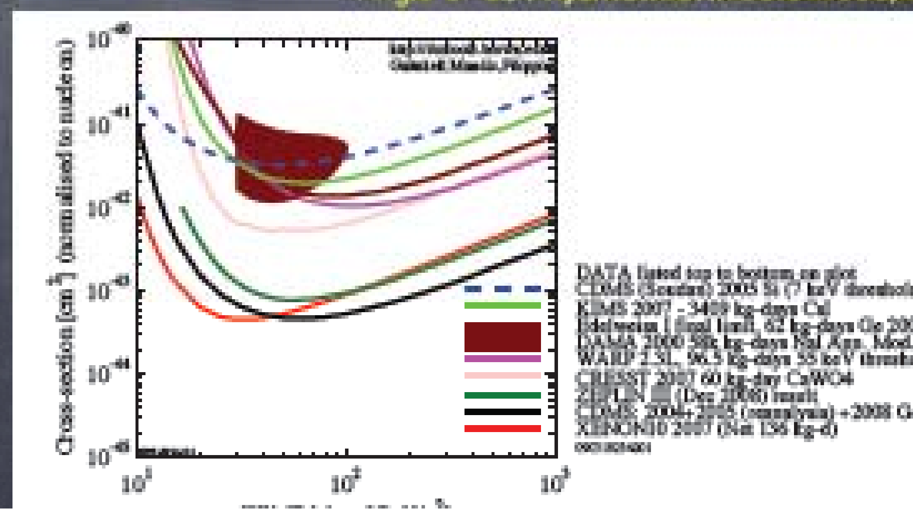




Angle et al., Phys.Rev.Lett.100:021303,2008

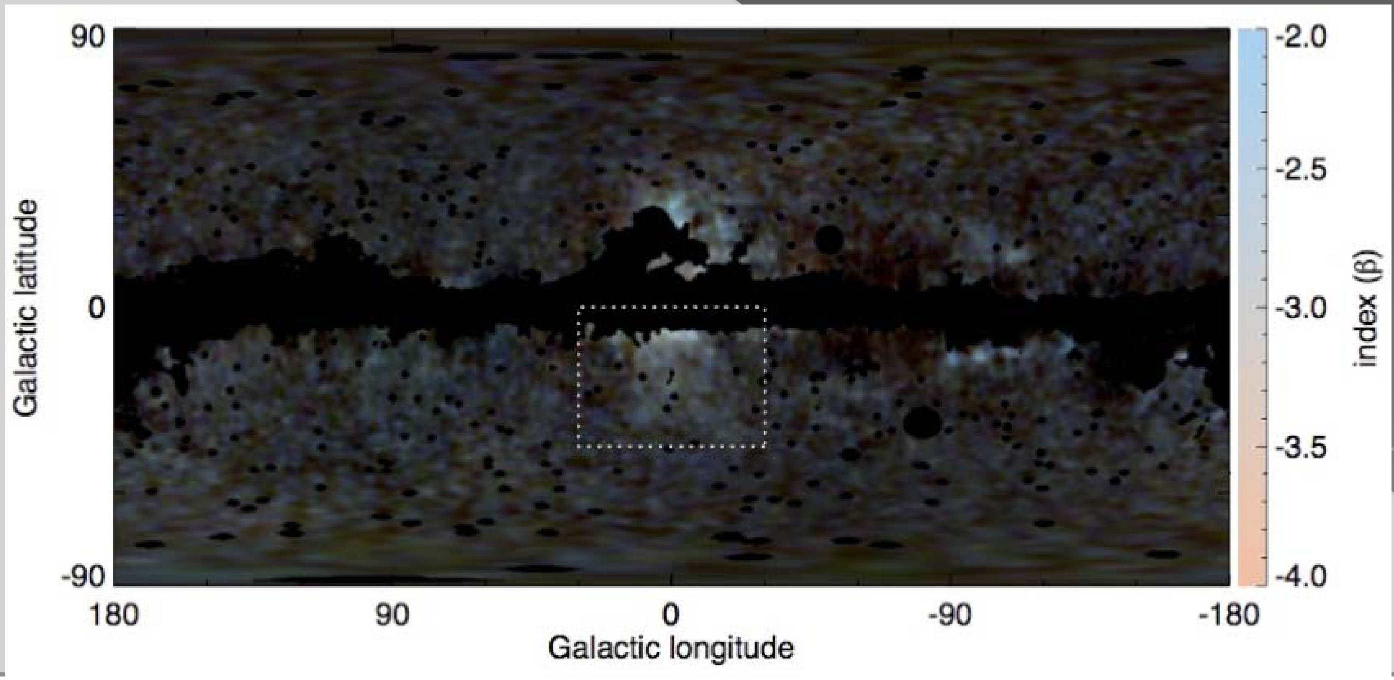
- 8.3 sigma signal for modulation
- only in "single hit" events
- proper phase

Dark matter?

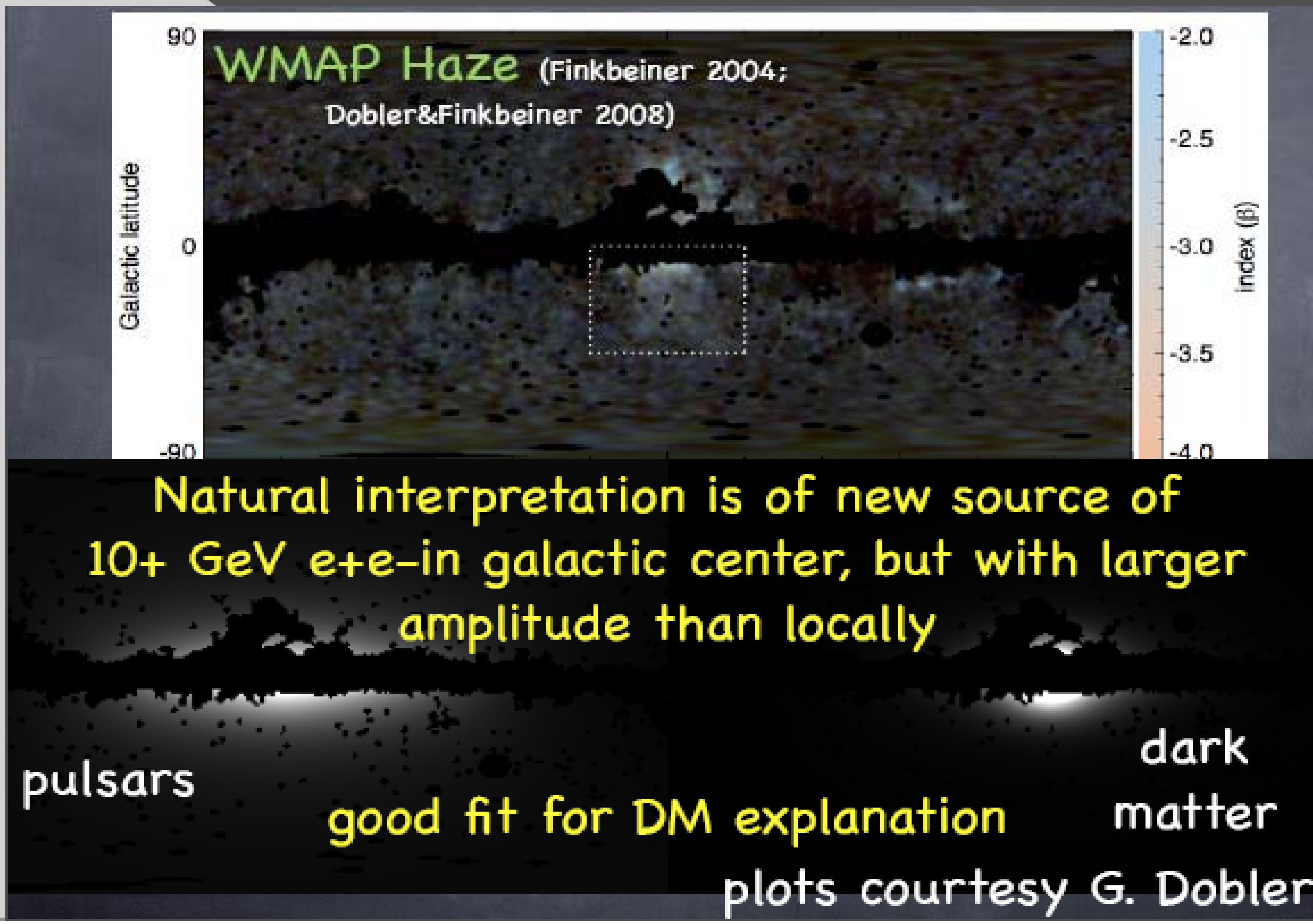


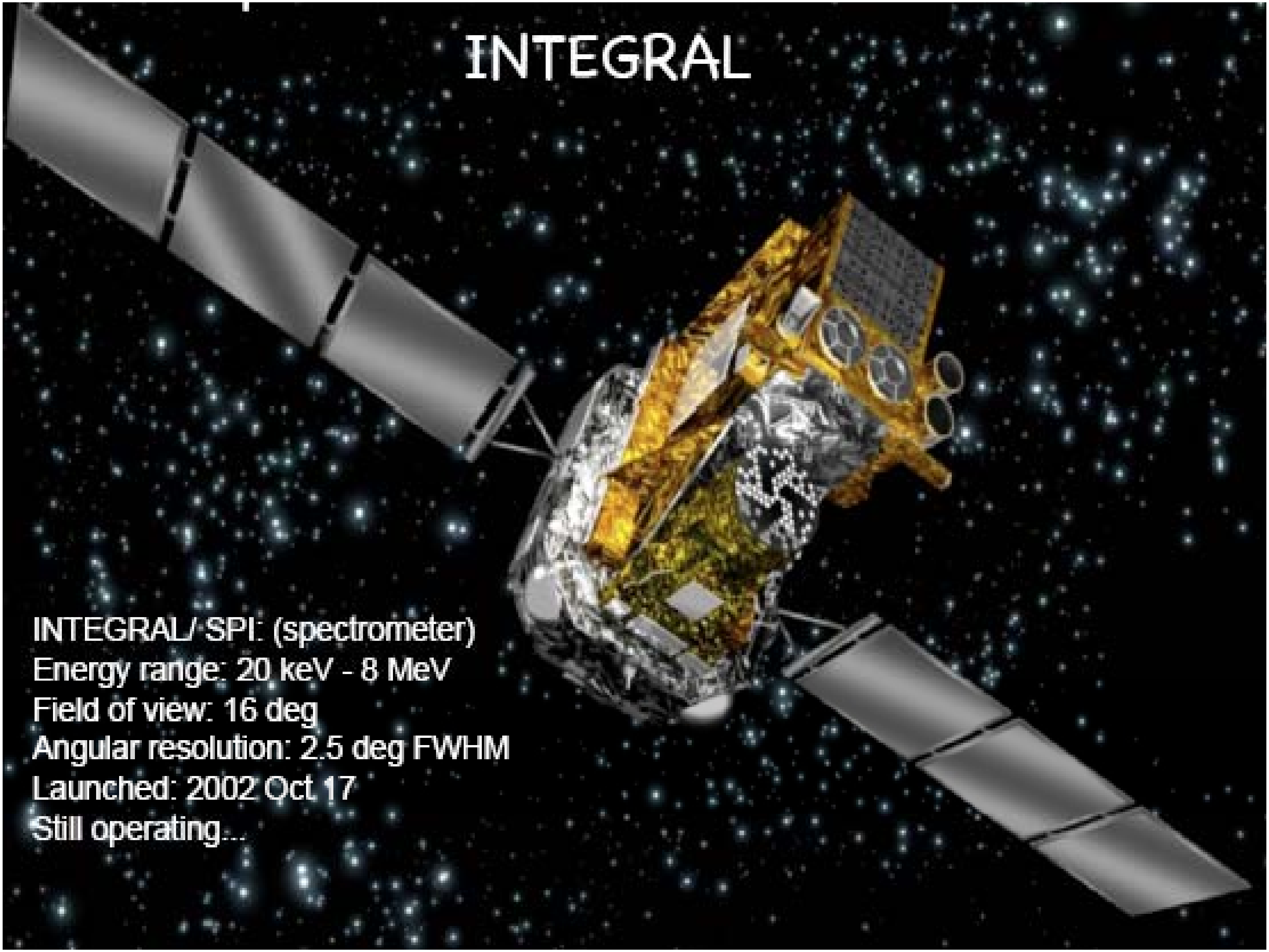
WMAP (Wilkinson Microwave Anisotropy Probe)

- Studies of the WMAP microwave emission from the galactic center show a hard component not spatially correlated with any known galactic emission mechanism.
- This "WMAP haze" (Finkbeiner, **Astrophys.J.614:186-193,2004**) can be explained as synchrotron radiation from electrons and positrons produced from dark matter annihilation in the galactic center .

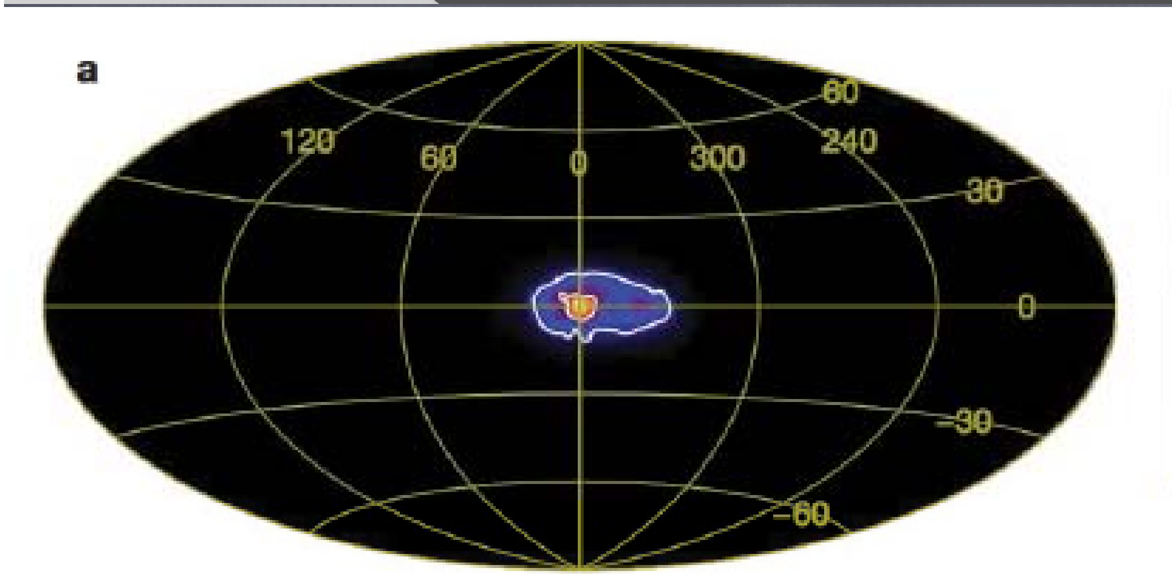


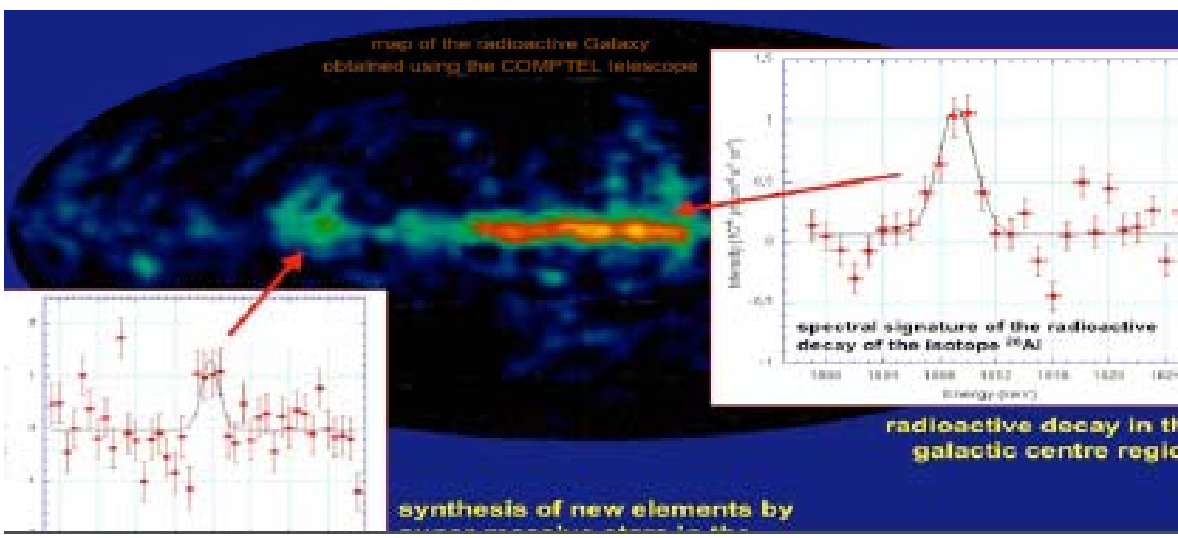
WMAP haze


WMAP Haze (Finkbeiner 2004;
Dobler&Finkbeiner 2008)
90
0
-90
Galactic latitude
-2.0
-2.5
-3.0
-3.5
-4.0
index (β)
Natural interpretation is of new source of
10+ GeV e+e- in galactic center, but with larger
amplitude than locally
pulsars
good fit for DM explanation
dark
matter
plots courtesy G. Dobler


INTEGRAL
INTEGRAL/ SPI: (spectrometer)
Energy range: 20 keV - 8 MeV
Field of view: 16 deg
Angular resolution: 2.5 deg FWHM
Launched: 2002 Oct 17
Still operating...

Distribution of the INTEGRAL 511 keV line





- Shows ~3×10^{42} e^+/s annihilating in the galactic center; far more than expected from supernovae
- Positrons must be injected with low energies to give narrow line shape

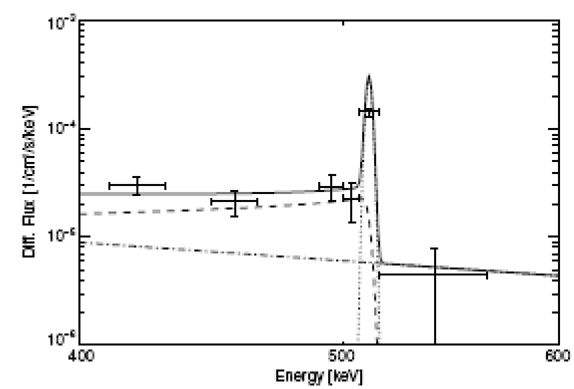
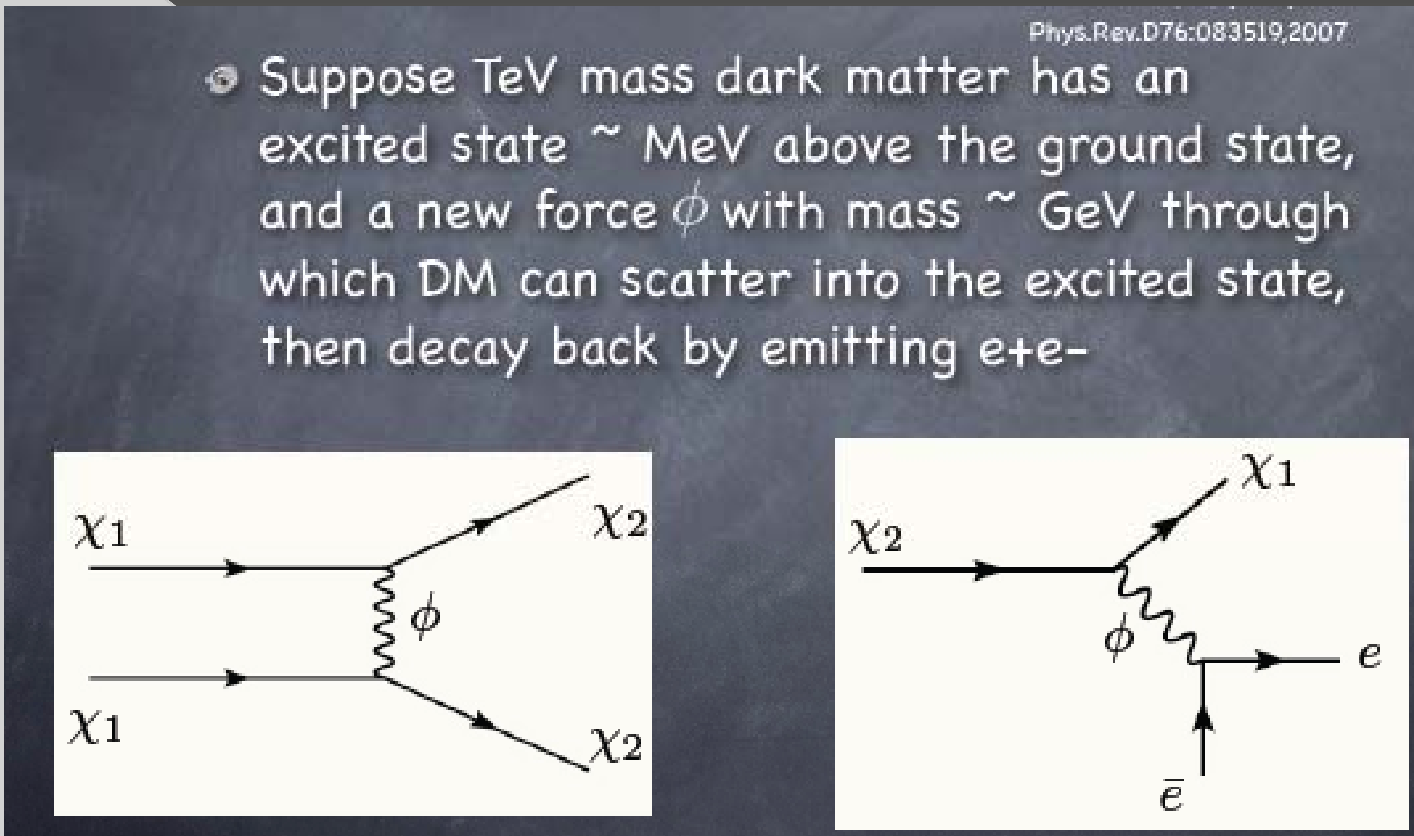


Fig. 2. A fit of the SPI result for the diffuse emission from the GC region ($|l|, |b| \leq 16°$) obtained with a spatial model consisting of an 8° *FWHM* Gaussian bulge and a CO disk. In the fit a diagonal response was assumed. The spectral components are: 511 keV line (dotted), Ps continuum (dashes), and power-law continuum (dash-dots). The summed models are indicated by the solid line. Details of the fitting procedure are given in the text.

eXiting Dark Matter (XDM)



Hypothesis by Finkbeiner&Weiner (2007). `Can naturally explain' low energy positrons with~ 1MeV excited states of the dark matter, while still producing the high-energy positrons via annihilation to explain PAMELA /ATIC data

Motivating Dark Forces

- A wealth of anomalies can be explained by the presence of a new, dark force
- Single ingredient: new dark force at ~ GeV addresses key issues
  - Large excitation cross section for INTEGRAL
  - Hard leptons/no antiprotons for PAMELA/Fermi
  - Large Annihilation cross section
  - Excited states for DAMA/INTEGRAL
- Testable
- See, e.g., Arkani-Hamed et al, PRD79, 015014 (2009)

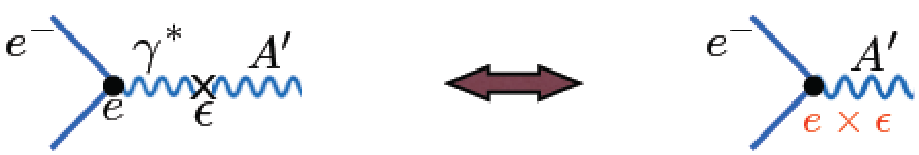
Searching for Dark Forces in Electron Fixed-Target Experiments

Natalia Toro

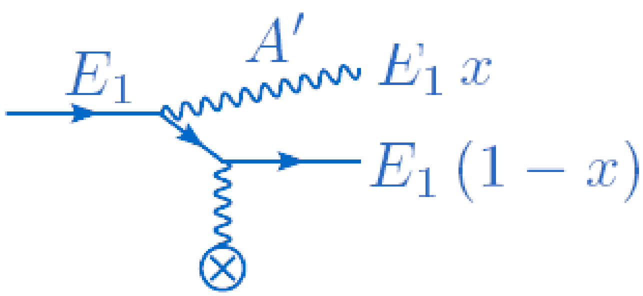
with J. D. Bjorken, R. Essig, and P. Schuster (0906.0580)
to appear in PRD

Phys.Rev.D80:075018,2009

- Dark gauge boson A´ mixing with photon, Mass $m_{A'}$ = 1 MeV – few GeV



Fixed-Target



- This vertex allows A´ production in any charged-particle scattering.

- Assume A´ decays (only) through photon mi
i.e. to e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$, etc. depending on mas
$c\tau \sim (m_{A'}\epsilon^2)^{-1}$

$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$

Constraints on mass vs coupling for A'

BJORKEN *et al.* PHYSICAL REVIEW D **80**, 075018 (2009)

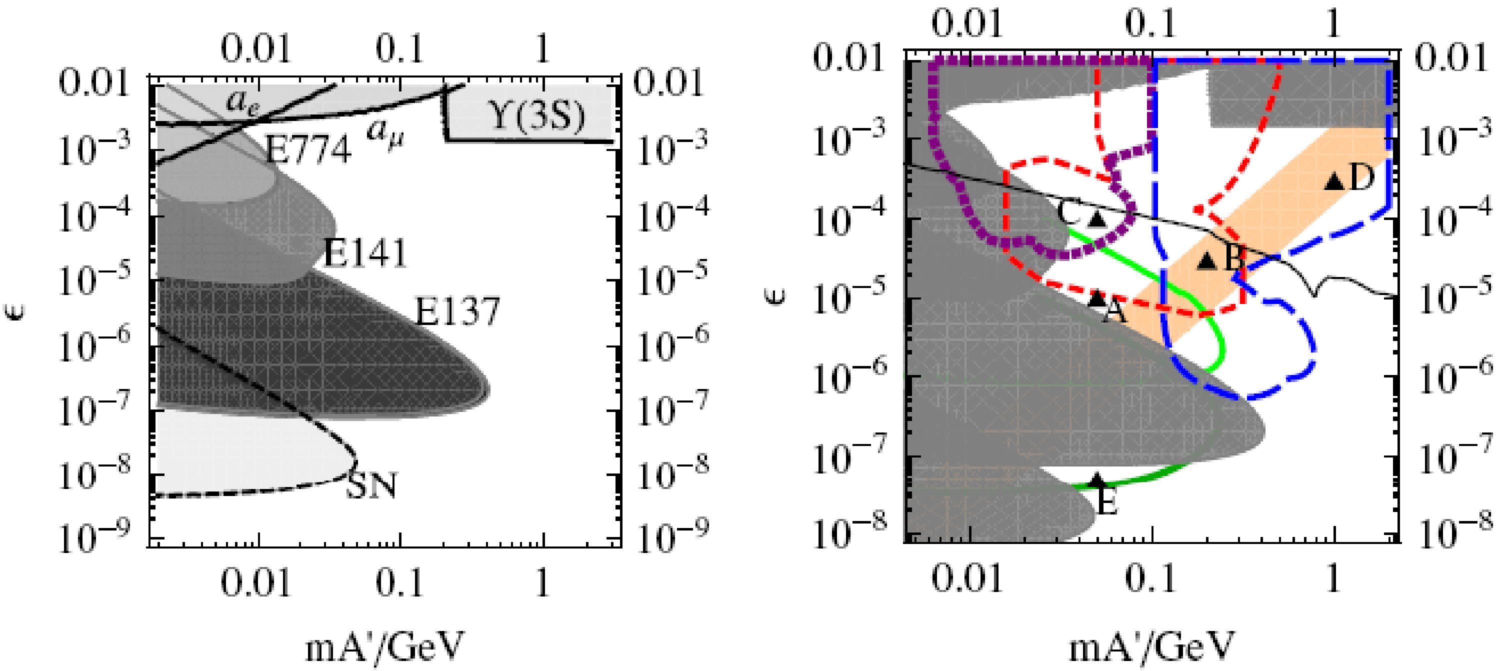
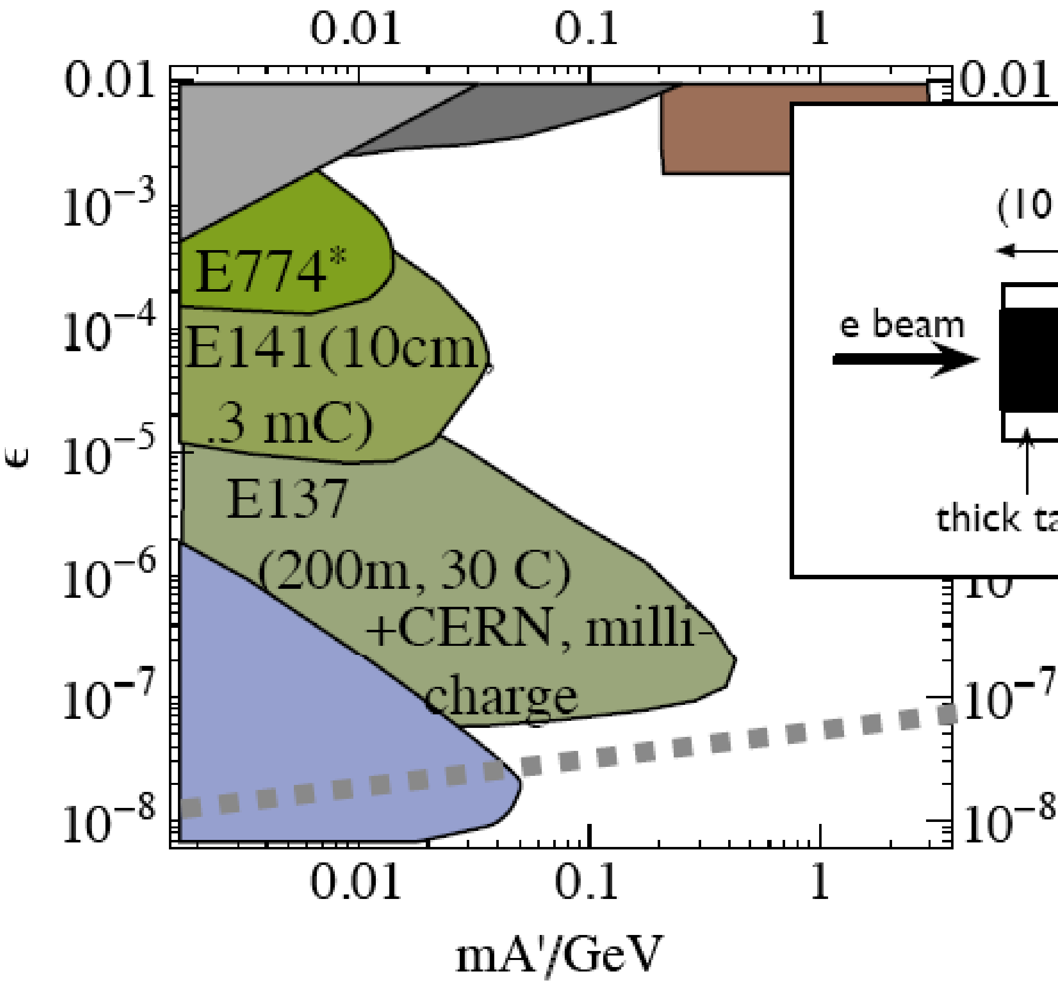
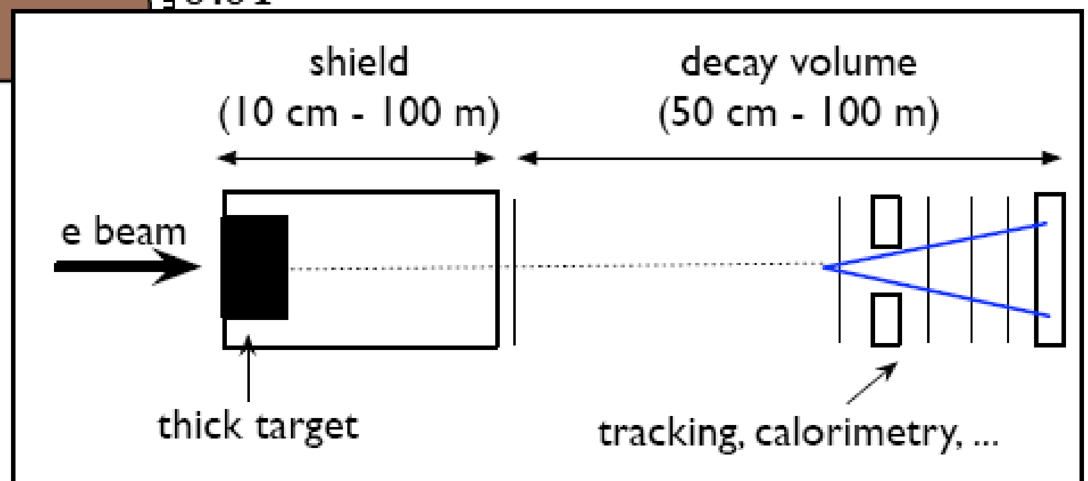


FIG. 1 (color online). *Left:* Existing constraints on an A'. Shown are constraints from electron and muon anomalous magnetic moment measurements, a_e and a_μ, the *BABAR* search for $\Upsilon(3S) \rightarrow \gamma\mu^+\mu^-$, three beam-dump experiments, E137, E141, and E774, and supernova cooling (SN). These constraints are discussed further in Sec. III. *Right:* Existing constraints are shown in gray, while the various lines—light green (upper) solid, red short-dashed, purple dotted, blue long-dashed, and dark green (lower) solid—show estimates of the regions that can be explored with the experimental scenarios discussed in Secs. IV A, IV B, IV C, IV D, and IV E, respectively. The discussion in Sec. IV focuses on the five points labeled "A" through "E." The orange stripe denotes the "*D*-term" region introduced in Sec. II A, in which simple models of dark matter interacting with the A' can explain the annual modulation signal reported by DAMA/LIBRA. Along the thin black line, the A' proper lifetime $c\tau = 80\ \mu$m, which is approximately the τ proper lifetime—see Eq. (11).

Searching in Dumps





MegaWatt x Year
lower limit

(dump experiments also constrain
longer-lived decay modes,
see Schuster, NT, Yavin to appear)

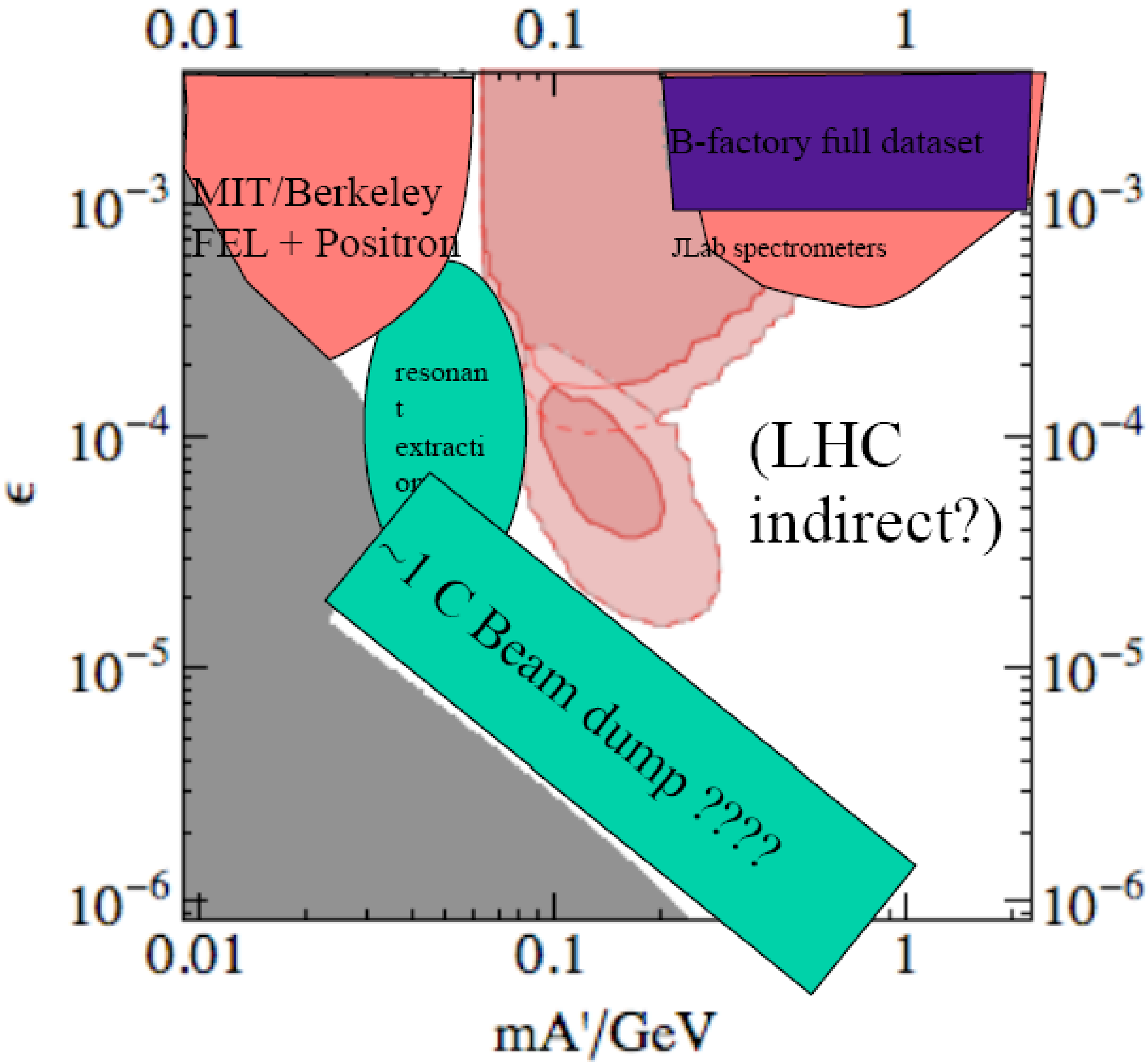
*E774: 20cm, .3 mC

JLAB experiments (to be proposed)

- Maruyama et al (Hall B photon dump)
- Wojtsekhowski (Hall A); also use positron beams
- Thaler, Fisher, Ent (Berkley, MIT, JLAB): Use gas jet target at Jlab FEL beam
- AA,Boyce, et al (FEL beam dump)

- Similar program at a newly proposed MESA facility at Mainz (Kurt Aulenbacher)

Reach



0.01
0.1
1
B-factory full dataset
MIT/Berkeley
FEL + Positron
JLab spectrometers
resonan
t
extracti
on
(LHC
indirect?)
~1 C Beam dump ????
10^{-3}
10^{-4}
10^{-5}
10^{-6}
ϵ
mA'/GeV

Discovery potential of fixed-target experiments

- Fixed-target experiments well suited to search fordark forces – high intensity
  - Also poses unique challenges
- Large parameter space requires multiple search strategies
  - Low coupling/mass: Beam dump experiments
  - High coupling/mass: standard wide-angle spectrometers (e.g. JLab)
  - Large intermediate region for new forward-geometryexperiments to explore