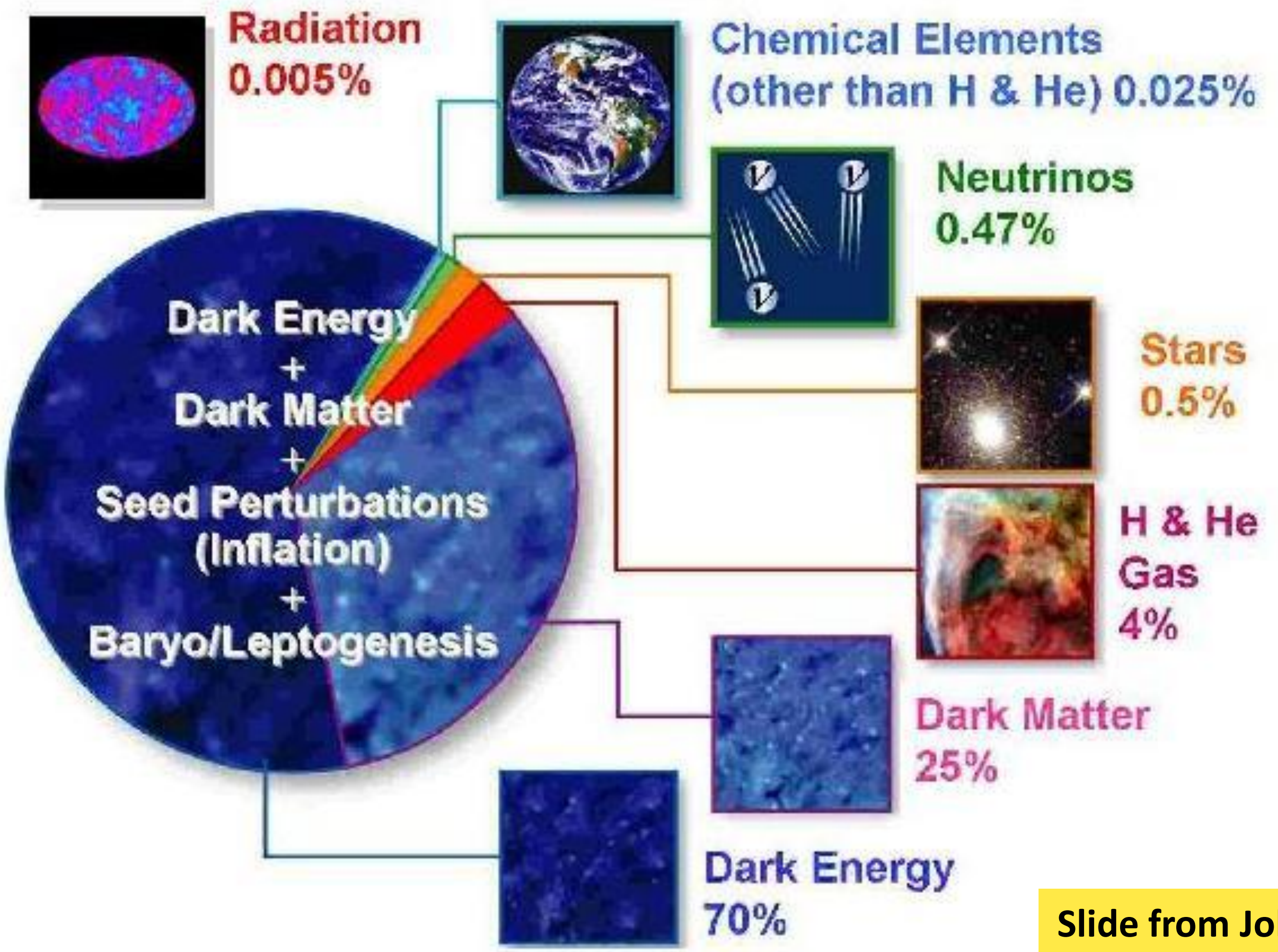
Call for a Superdark Moose in a Hidden Valley

1. Review of observed anomalies
2. Introduction to a new “Theory of Dark Matter”
3. Signatures at running or stalled colliders

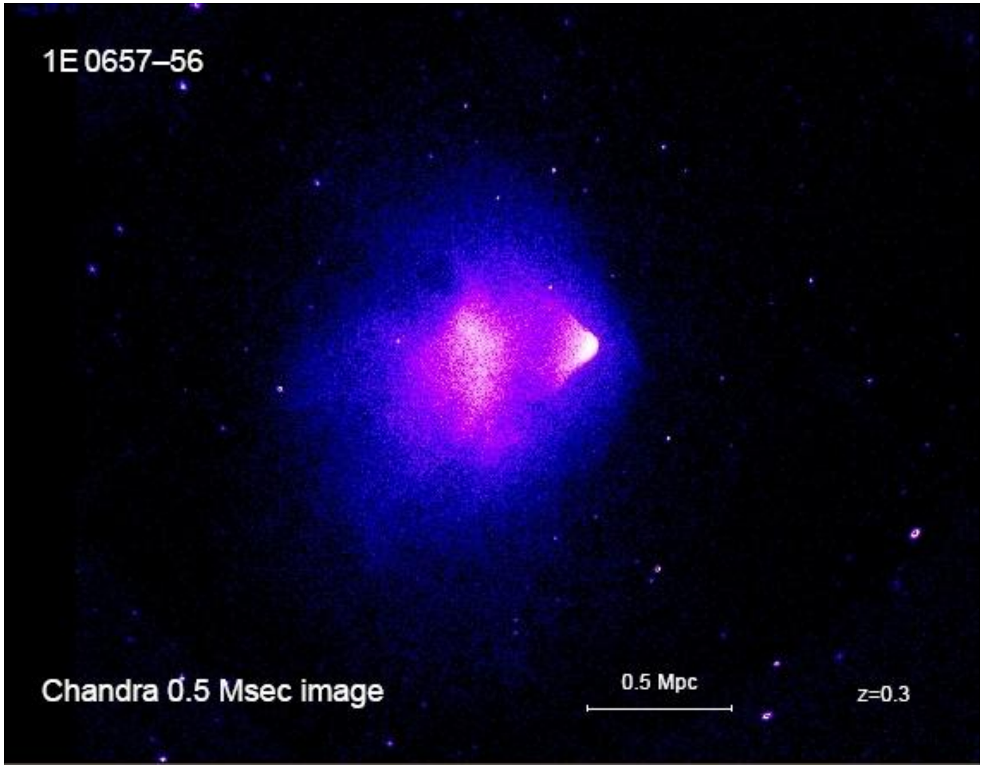
Pauline Gagnon, Indiana University

Is there something beyond the Standard Model ? Yes, and dark matter is the best proof!



Slide from John Ellis

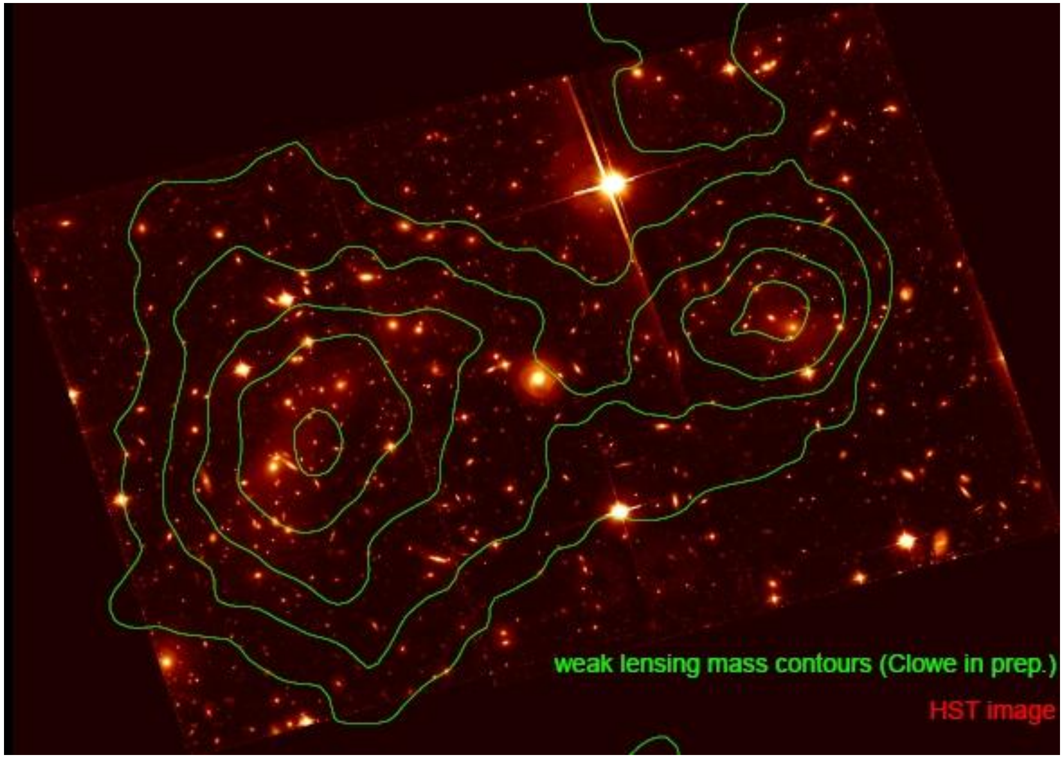
Proof that dark matter exists: the bullet cluster



Exposition time: 140 hours!
Picture is 1.6 light-year wide

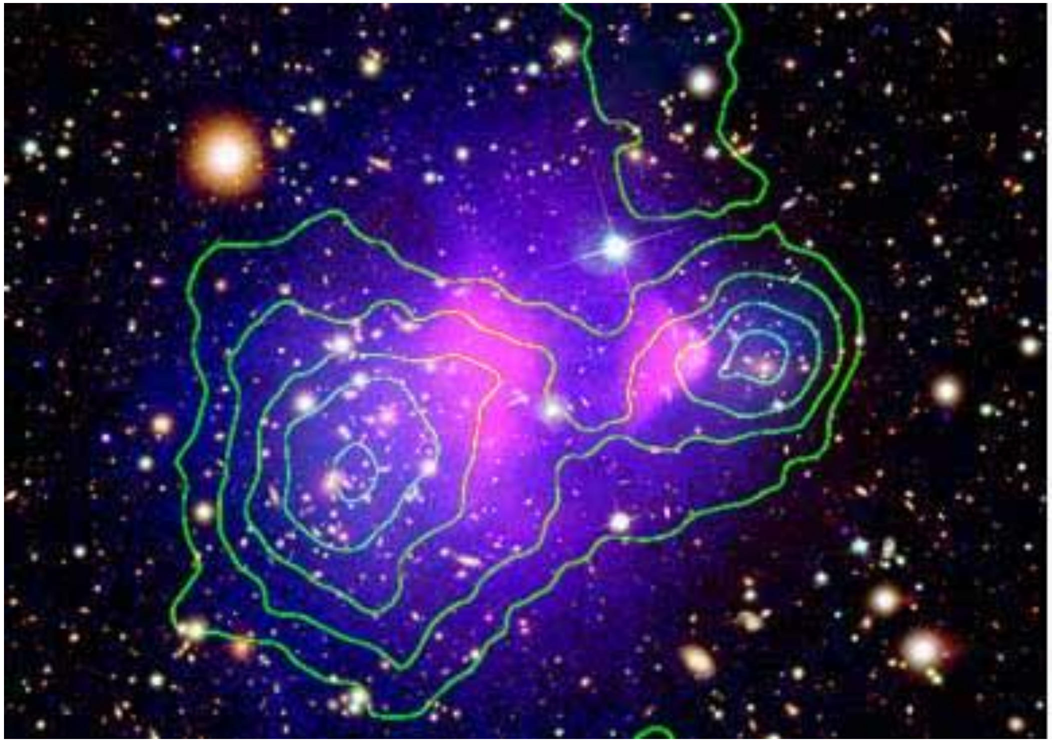
- Picture of two galaxy clusters hitting each other
- What collides is the inter-galactic material (gas)
- It heats up to 160×10^6 °C then emits X-rays
- What we see here is the intensity of X-rays emission

Dark Matter is seen by Weak Gravitational Lensing



- Same event seen by the Hubble telescope through gravitational lensing
- Dark matter from each cluster passed over each other without interacting
- Shows the contours of gravitational field caused by dark matter

So dark matter is there but interacts very weakly



Inter-galactic gas clouds collided but the dark matter kept moving on

Center of gravity for visible matter and dark matter different

What is this dark matter?

Could it explain many observed astrophysics anomalies?

Six observed, unexplained anomalies from astrophysics

<u>High energy anomalies</u>

1. PAMELA/HEAT
2. ATIC
3. WMAP haze
4. EGRET

<u>Low energy anomalies</u>

1. INTEGRAL
2. DAMA/LIBRA

1. The PAMELA/HEAT anomaly:

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

- observed positron flux from cosmic rays $\phi_{e^+} / (\phi_{e^+} + \phi_{e^-})$ larger than expected;
- first seen by HEAT; confirmed by PAMELA
- no such excess seen for protons
- could come from high energy cosmic ray interactions with interstellar medium; or could be due to nearby mature pulsars

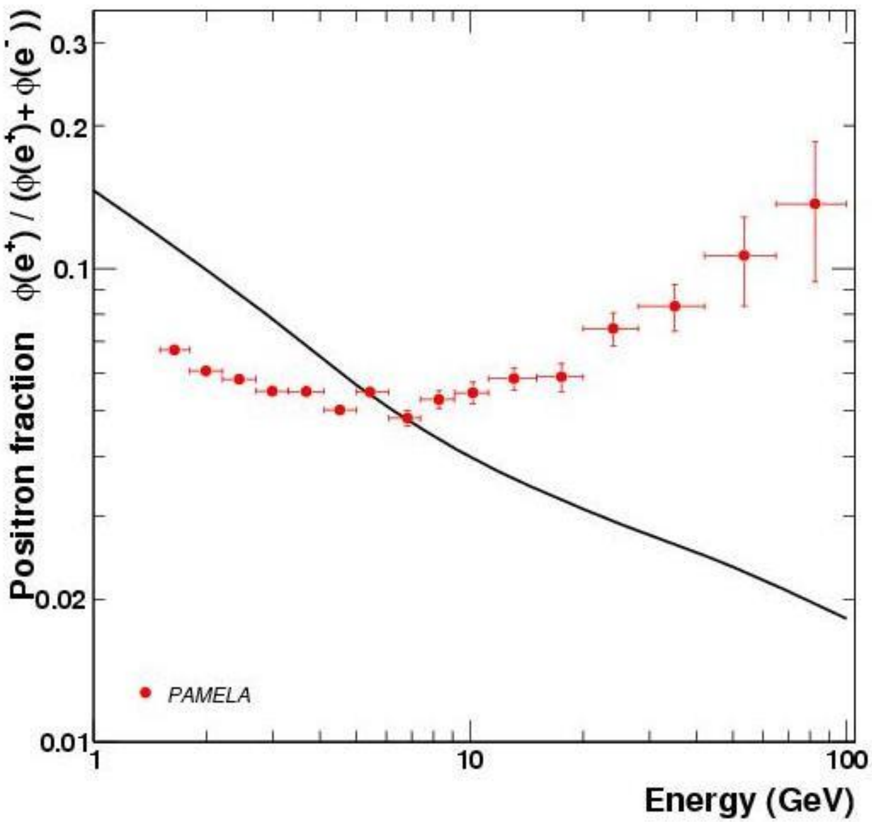
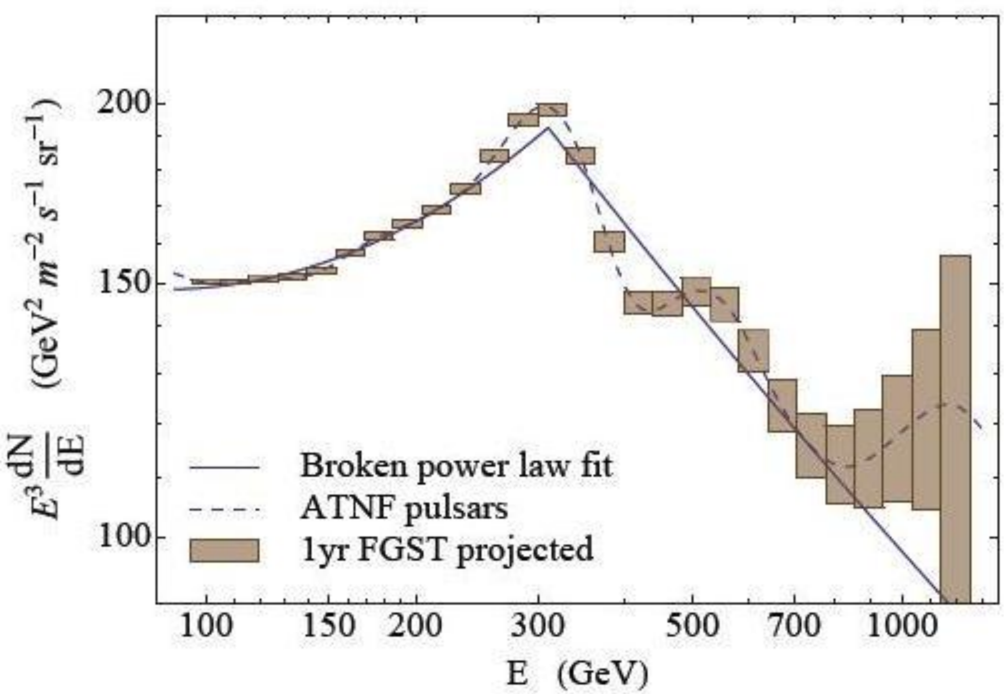


FIG. 4: **PAMELA positron fraction with theoretical models.** The PAMELA positron fraction compared with theoretical model. The solid line shows a calculation by Moskalenko & Strong[39] for pure secondary production of positrons during the propagation of cosmic-rays in the galaxy. One standard deviation error bars are shown. If not visible, they lie inside the data points.

Pulsar or Dark Matter? Fermi may tell



ATNF: catalog of all known pulsars

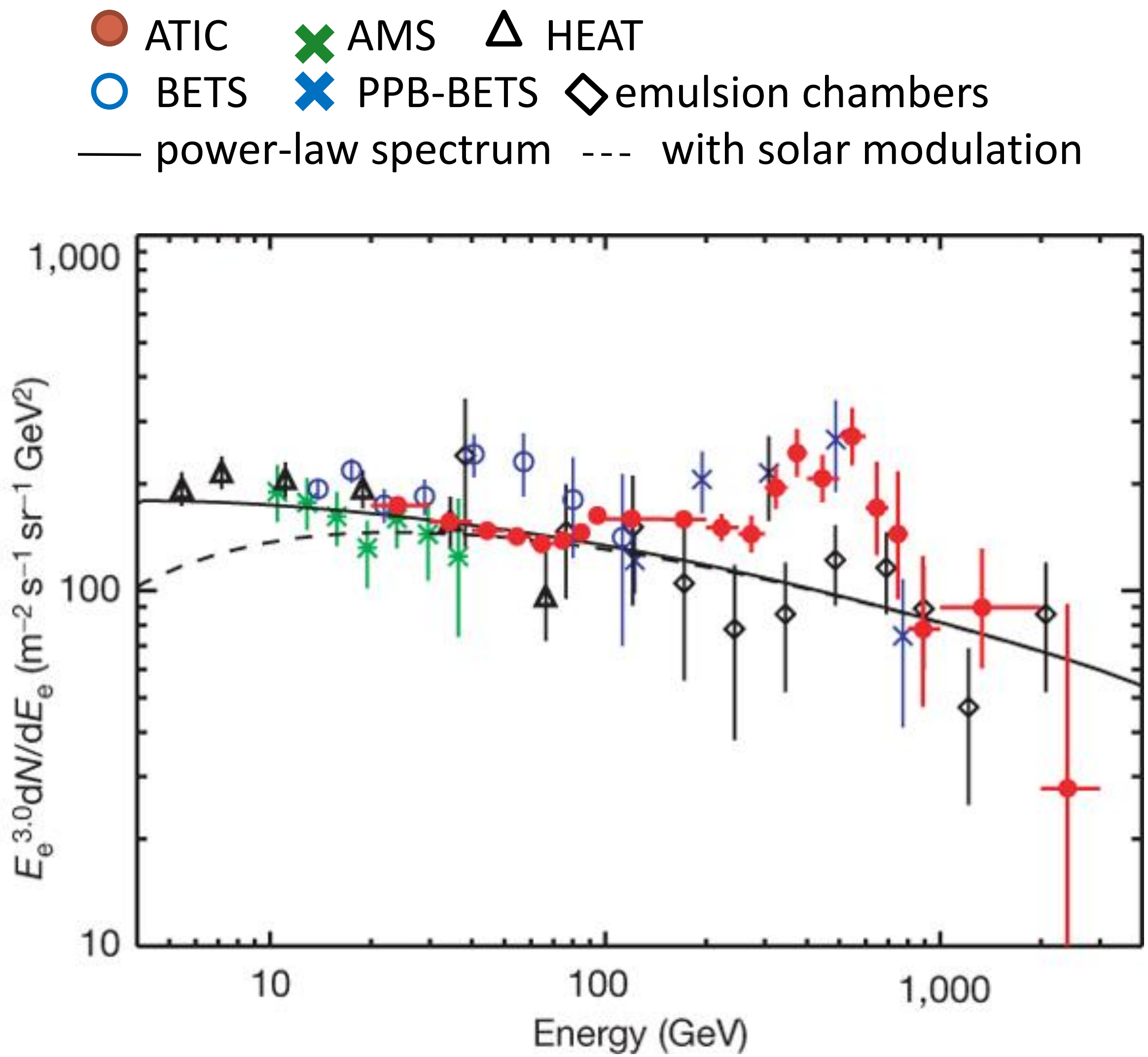
- Flux from pulsar characterized by steps
- DM would give a power law spectrum
- Malyshev, Cholis & Gelfand suggest Fermi could resolve this with one year of data (arXiv:0903.1310)

2. The ATIC anomaly:

(**ATIC**: Advanced Thin Ionization Calorimeter; balloon experiment above Antarctica)

excess in cosmic ray electron flux at 300-800 GeV

FERMI will soon release its data on this

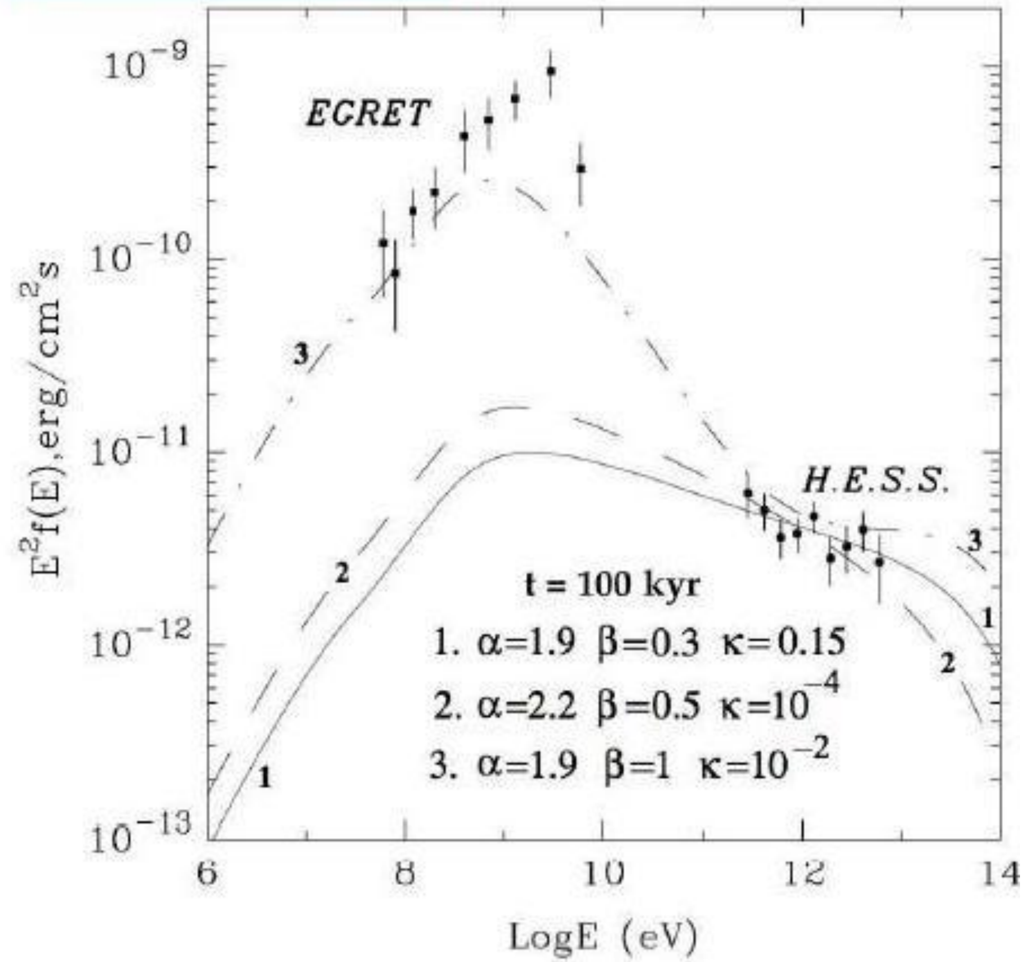


Nature 456, 362-365 (2008)

3. **EGRET:**

- γ-ray measurements in galactic center shows excess at 10-50 GeV
- Same amount of data will be collected by FERMI in one year of data
- FERMI will reach 25 times EGRET sensitivity
- FERMI launched June 2008 – first data reported in Moriond

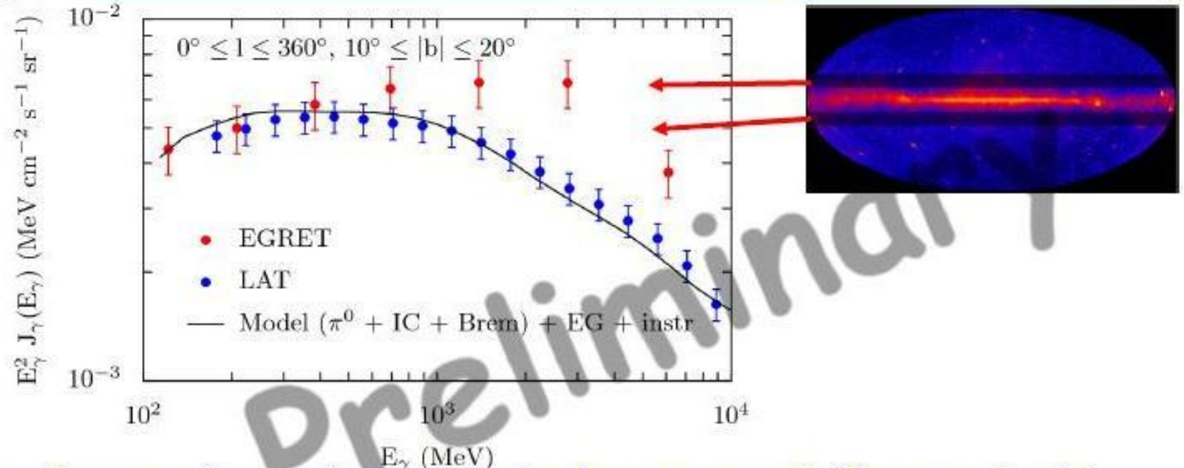
Aharonian-Neromov 2006



First results from Fermi: EGRET excess not confirmed

Fermi-LAT

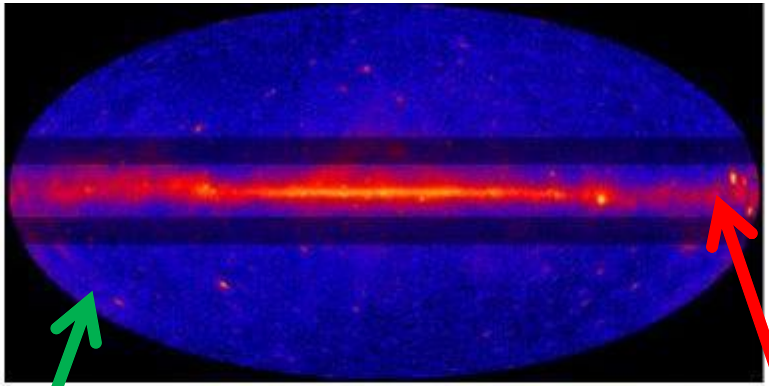
The Fermi LAT View



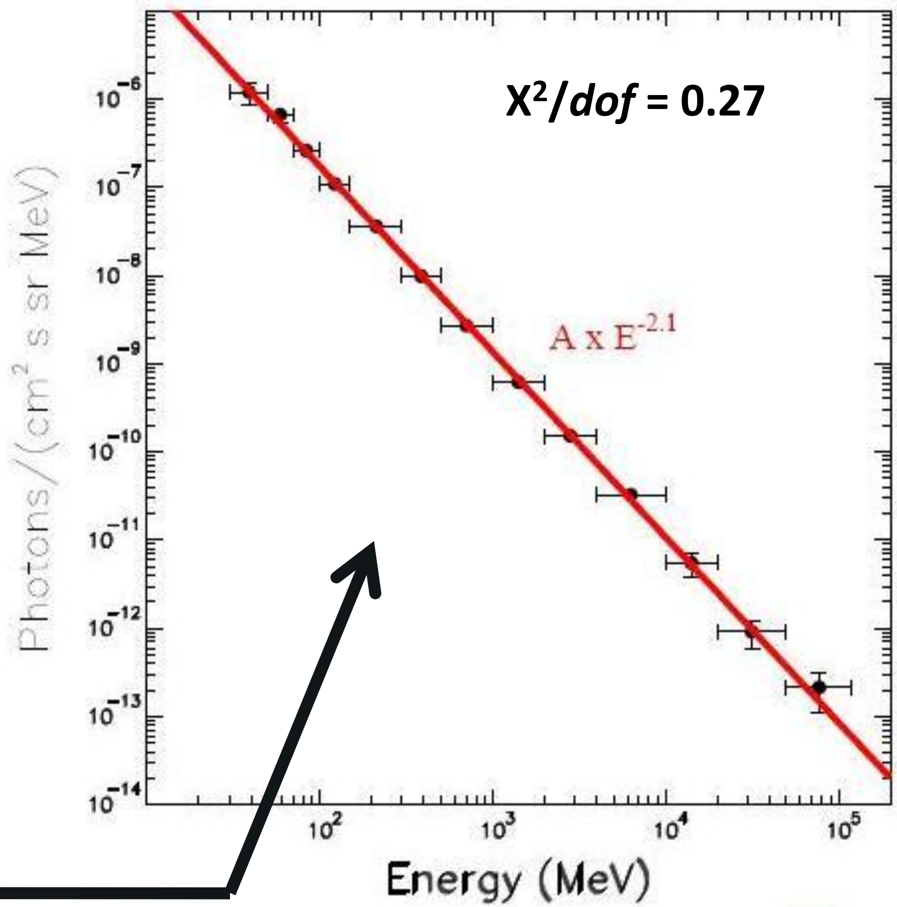
- Spectra shown for mid-latitude range -> GeV excess in this region is not confirmed.
- LAT errors are dominated by systematic uncertainties and are currently estimated to be ~10% - this is preliminary.
- EGRET data is prepared as in Strong, et al. 2004 with a 15% systematic error assumed to dominate (Esposito, et al. 1996).

Guðlaugur Jóhannesson for the Fermi LAT collaboration XLIVth Rencontres de Moriond – La Thuile, Italy, February 2009 14

Fermi and EGRET agree at large latitudes



- EGRET and Fermi **disagree** on data from galaxy center
- **Agree** on diffuse γ-ray background radiation (GBR) at large latitudes
- GBR spectrum follows a simple power law

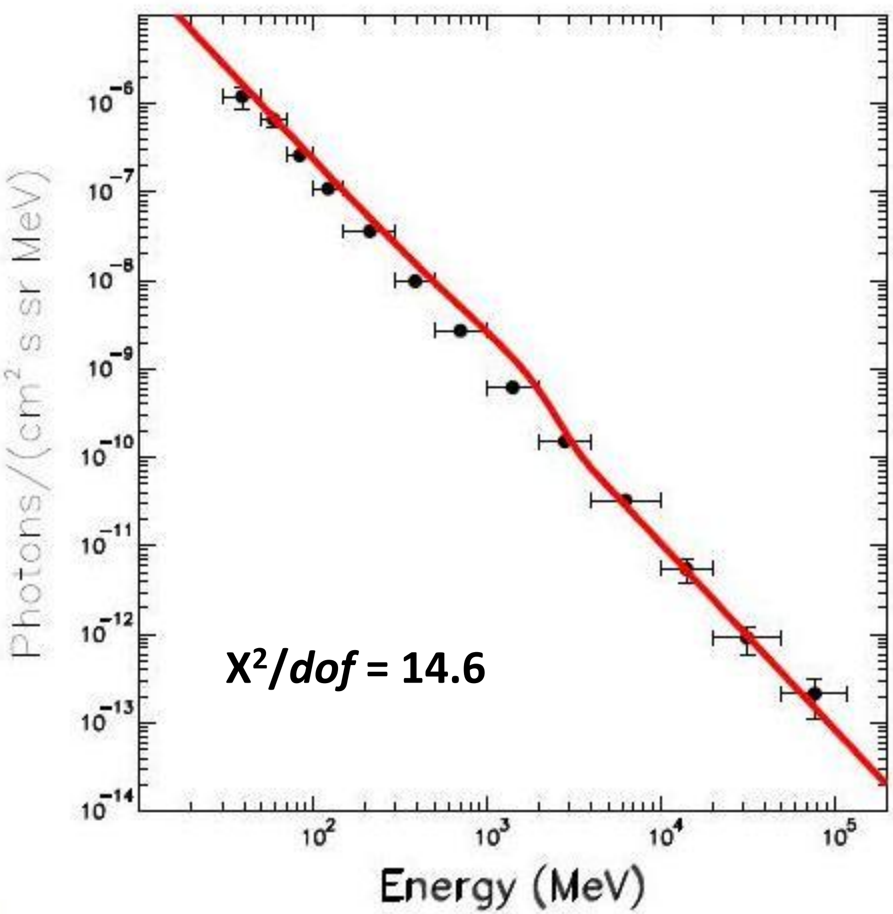


arXiv:0903.0165v1

Dado and Dar argue ATIC is also wrong!

arXiv:0903.0165v1

- ATIC sees electron flux excess at 500-800 GeV coming from no particular direction
- This should create diffuse γ-ray background radiation (GBR) at 0.8-2 GeV
- This does not fit in with the EGRET GBR data



4. **WMAP haze at the Galactic Center**:

(Wilkinson Microwave Anisotropy Probe)

- a diffuse microwave excess observed by WMAP from the core of our galaxy but not coming from a particular source point
- several distinct bands of diffuse radiation from the core of the galaxy spanning over 12 orders of magnitude in frequency.
- high energy gamma ray could be due to synchrotron radiation coming from dark matter annihilation into e+ and e-

5. SPI/INTEGRAL: International Gamma-Ray Astrophysics Laboratory, Ge detector array

- Observation of a 511 keV line from the galactic center –nothing from the galactic disk
- First seen in 1970 at 473 ± 30 keV
- Means large e+e- annihilation rate
- **Origin of galactic positrons unknown**
- Astrophysical sources could be neutron stars or black holes, radioactive nuclei from supernovae, cosmic ray interactions with the interstellar medium, pulsars etc.

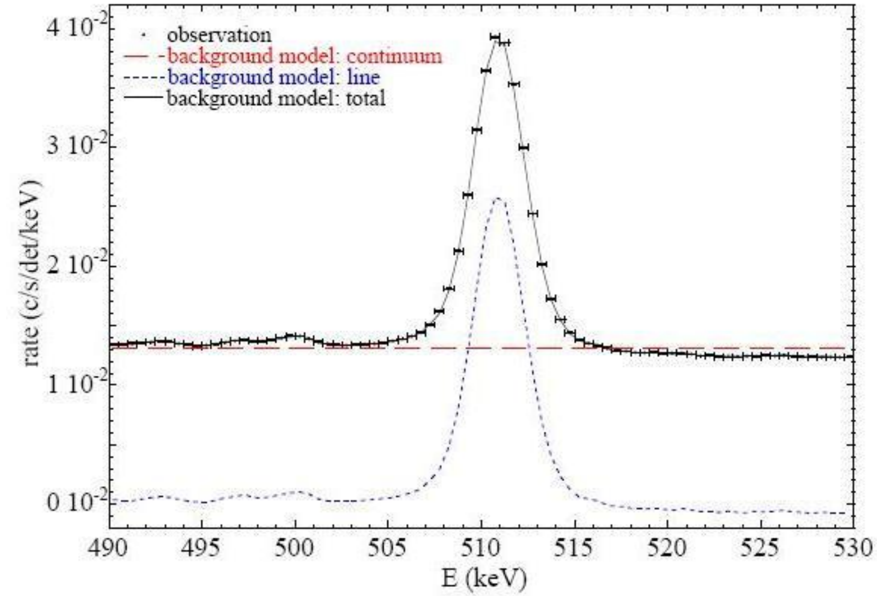
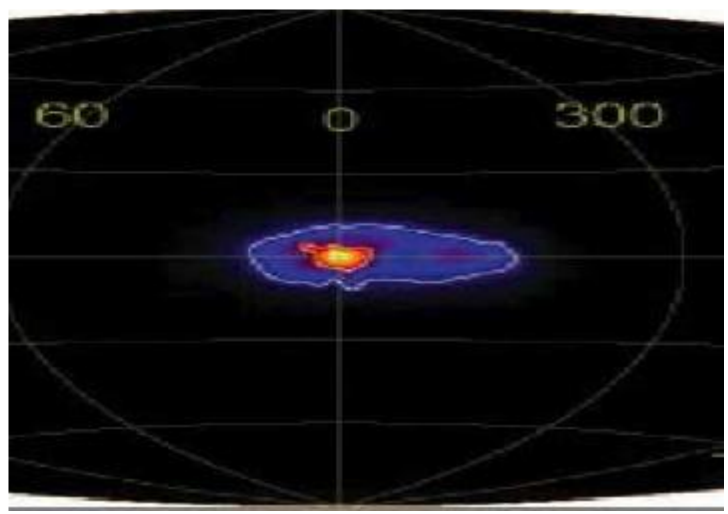


Fig. 1. Raw spectrum and background model components.

arXiv:astro-ph/0309442
arXiv:astro-ph/0309484



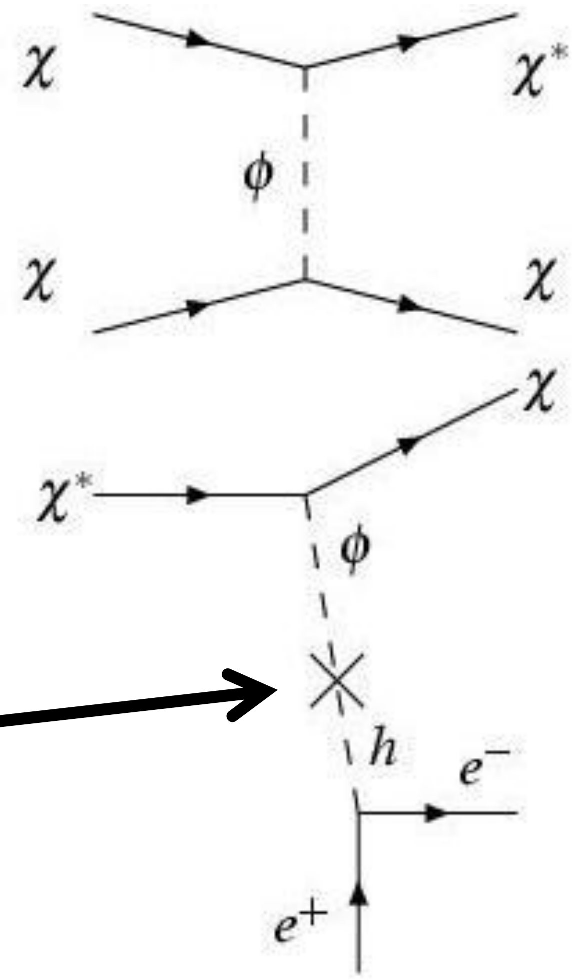
Not a symmetric source

Excited dark matter to explain INTEGRAL (Finkbeiner and Weiner astro-ph/0702587)

- If dark matter has a mass m_χ ~ 500 GeV, a dark matter particle travelling at a speed of 500 km/s carries kinetic energy > 511 keV
- If dark matter χ has excited state, χ*, it can get excited by inelastic scattering when bumping into each other
- χ* de-excite by emitting a e^+e^- pair → source of positrons
- The whole Milky Way is a vast reservoir of WIMP with kinetic energy ~ 10^{60} erg
- The 511 keV line radiates 5 x 10^{36} erg/s
  - This has not made a dent even over the life span of the Universe!
- All 511 keV emission comes from galactic center where dark matter is concentrated
- Satisfies the relic abundance seen today

Diagrams for excited dark matter

- Excited dark matter model also calls for a new light gauge boson in dark sector, ϕ
- ϕ can also decay into e^+e^-



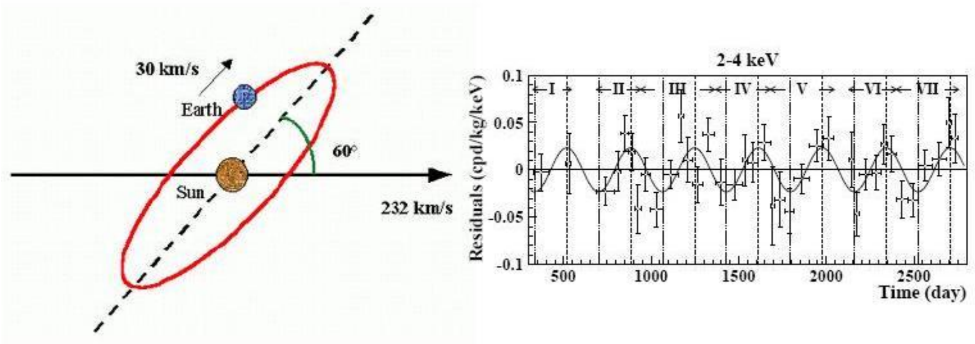
represents mixing

6. **DAMA/LIBRA**

- NaI scintillator experiment in Gran Sasso
- 1st exp: DAMA: claims presence of Dark Matter particles in the galactic halo (7 yrs of data: 0.29 ton-year)
- 2nd exp: DAMA/LIBRA: 0.53 ton-year
- 8.2σ deviation for the cumulative exposure
- No other source of modulation found
- Other similar experiments have null results (EDELWEISS, EDMS)

Graciela Gelmini-UCLA

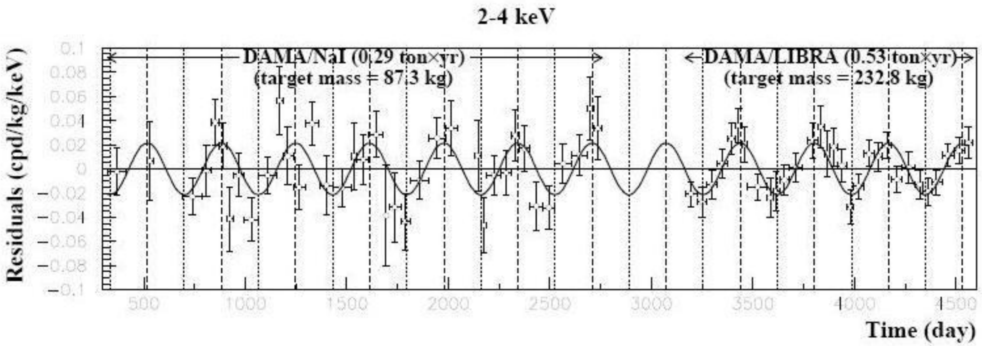
DAMA: DM signal?



7years of DAMA/NaI showed a 6σ modulation signal.

Graciela Gelmini-UCLA

DAMA+LIBRA 11 years, 0.83 ton $\times$ year, 8.2σ modulation signal.



arXiv:0804.2741

Inelastic dark matter scattering
(see arXiv:0903.3941v1 for a nice summary)

$\chi N \rightarrow \chi^* N$ with $\delta = m\chi^* - m\chi \sim 100$ keV

- For inelastic scattering to take place, the center-of-mass energy must exceed the mass splitting
  - Dark matter does not scatter for velocity below

$$v_{min} \sim (2\,\delta/\mu)^{1/2}$$

μ is the nucleon-dark matter reduced mass

- This minimum velocity increases for small nucleus mass like iodine used by DAMA/LIBRA but would not be reached for Germanium used by CDMS or Edelweiss
- Inelastic dark matter proposed by D. Tucker-Smith and N. Weiner Phys. Rev. D76 (2007) 083519

Could these anomalies have something in common?

- Some of these anomalies might be flukes (EGRET for example)
- Some have alternative astrophysical explanations
- But they could also all have something to do with dark matter:

- Dark matter annihilation gives rise to high energy e+ and e- to explain PAMELA and ATIC
- WMAP: high energy gamma ray could be due to synchrotron radiation associated with these energetic e+ and e-
- For DAMA to be compatible with other experiments null results, we need inelastic dark matter model (IDM)
- For INTEGRAL, exciting dark matter is needed (XDM)
- Both XDM and IDM require dark matter mass splitting

One size fits all?

- That’s the goal of “A theory of Dark Matter”

  Arkani-Hamed, Finkbeiner, Slatyer, Weiner arXiv:0810.0713v2
- How to solve simultaneously high energy problems and low energy phenomena?
- One way is to come up with two new particles:
  - One dark matter particle with a high mass to solve high energy anomalies
  - Add mass splitting to explain low energy anomalies
  - One low mass gauge boson comes naturally into play

Explains both high energy and low energy anomalies

High energy:

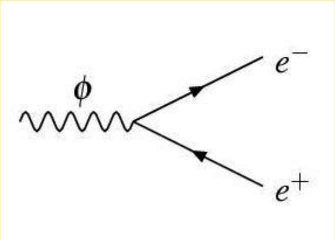
- A Weakly Interacting Massive Particle (WIMP) χ with m_χ ~ 500-800 GeV to explain high energy data
- Dark matter χ could annihilate into a light boson ϕ:

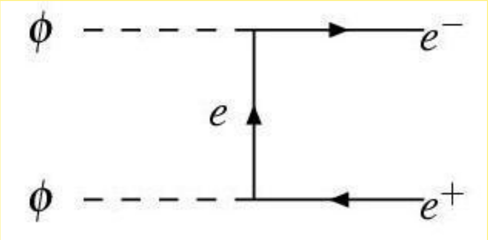
$$\chi\chi \rightarrow \phi\phi$$

$$\phi \rightarrow e^+e^- \text{ or } \mu^+\mu^-$$

- Provides a source of high energy positrons and electrons (ATIC, PAMELA)
- These can also generate high energy photons by synchrotron radiation (WMAP)

- ϕ could be so light that it can only decay into leptons
- ϕ is a new force carrier with m_ϕ ~ 100 MeV-1 GeV





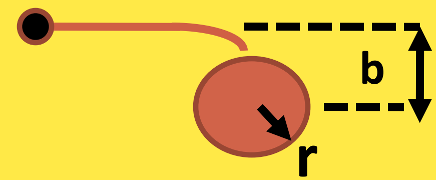
Low energy:

- Impose that dark matter has excited states with small mass splitting for χ
- Then the requirements of exciting dark matter needed for INTEGRAL and of inelastic dark matter for DAMA are both satisfied

A Theory of Dark Matter

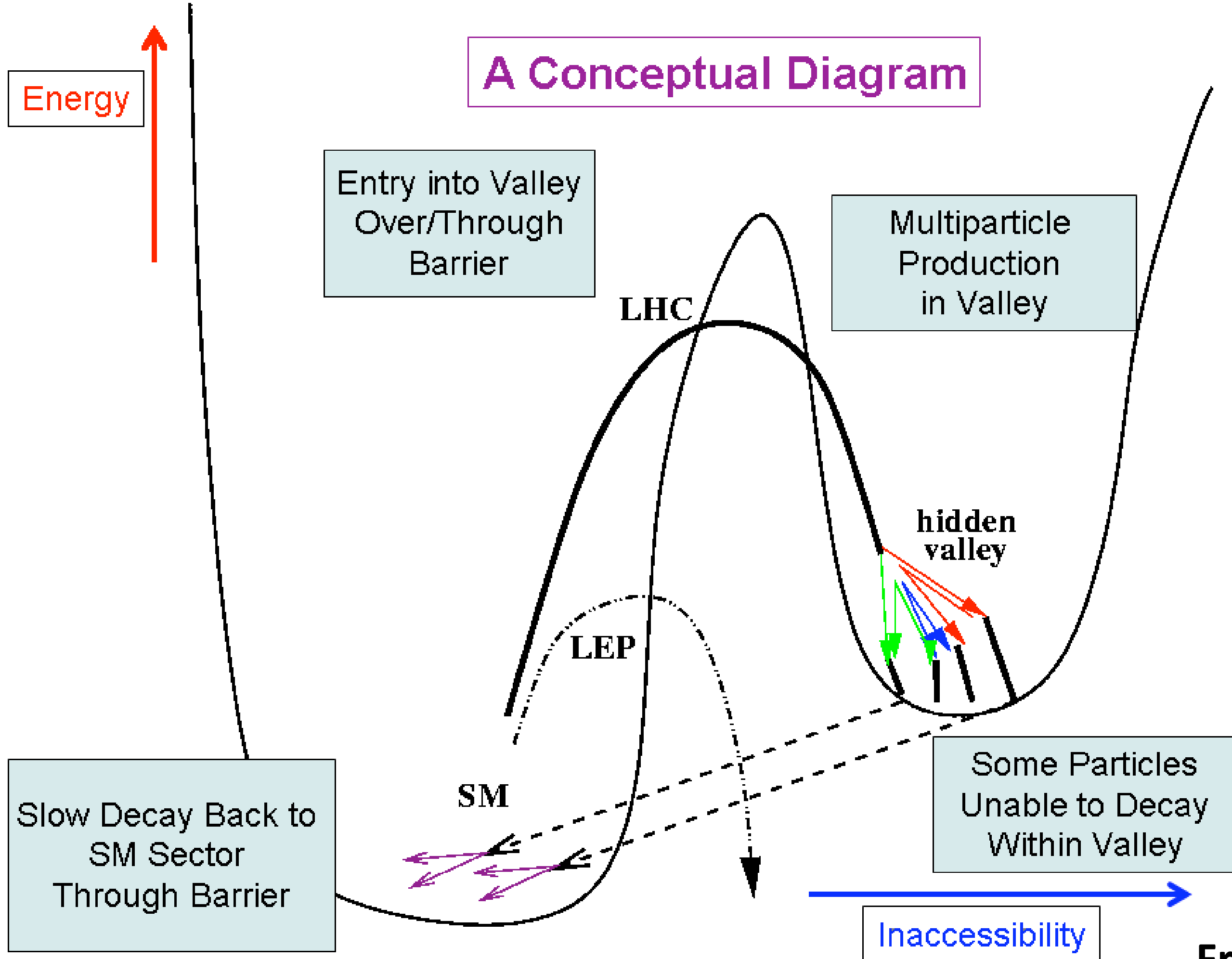
- They start from what's needed to explain PAMELA and ATIC data and impose constraints such as satisfying the PAMELA rate and observed amounts of dark matter seen today
- They argue that a dark matter particle χ , m_χ= 500-800 GeV cannot be the lightest supersymmetric particle (LSP)
- Naturalness arguments bring in the need for a low mass new gauge boson: ϕ, $m_\phi \sim$ 1GeV
- This allows them to get a Sommerfeld enhancement of the annihilation cross-section for $\chi\,\chi \rightarrow \phi\phi$ needed to explain the relic abundance i.e. what is seen today

Sommerfeld enhancement:



- Quantum mechanism needed to provide an enhancement (~ 100 times larger) for the dark matter annihilation rate. The usual WIMP cross-section is too weak to explain the current observations.
- Classical analogy: cross-section for an object to hit a star of radius r is πr^2 but this cross-section will increase if gravity is present to be πb^2, where b is the distance-of-closest approach for capture.
- Sommerfeld enhancement: arises when a particle has an attractive force carrier with a Compton wavelength > $(\alpha M_{DM})^{-1}$, α: Dark Matter coupling.

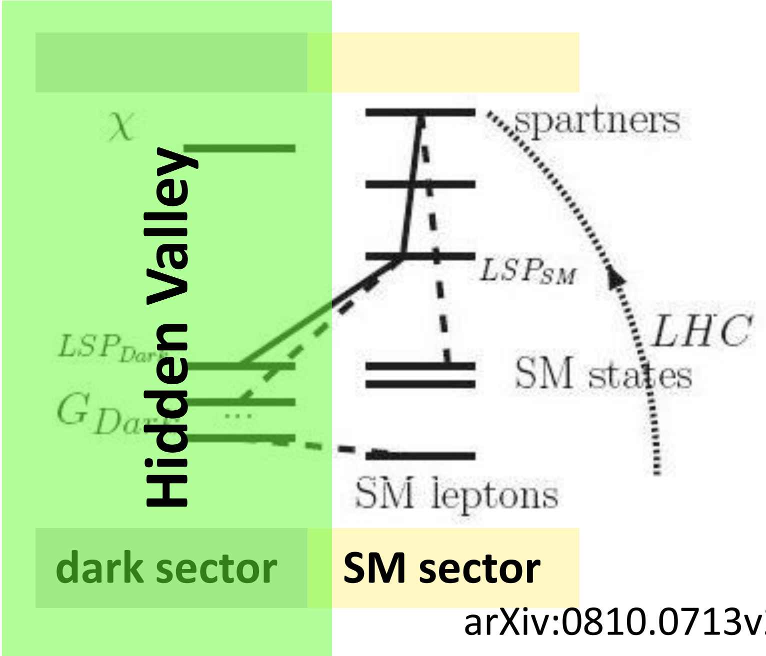
A schematic view of Hidden Valley model



From M. Strassler, adapted by H. Lubati

New picture

- Two parallel worlds:
  - SM + SUSY
  - Dark sector also with $SUSY_{dark}$
- At LHC, we can produce the highest SUSY states in SM sector
- These will cascade down to LSP_{SM} but this is not the real LSP (lightest supersymmetric particle)
- The LSP_{SM} is a messenger that can cross-over to the dark sector then decay into the true LSP, the LSP_{dark}
- On the dark sector side, many χ states
- The dark matter particle χ is not the LSP
- ϕ is the lightest state
- LSP_{dark} (our ϕ) is also a messenger and will decay into SM particles



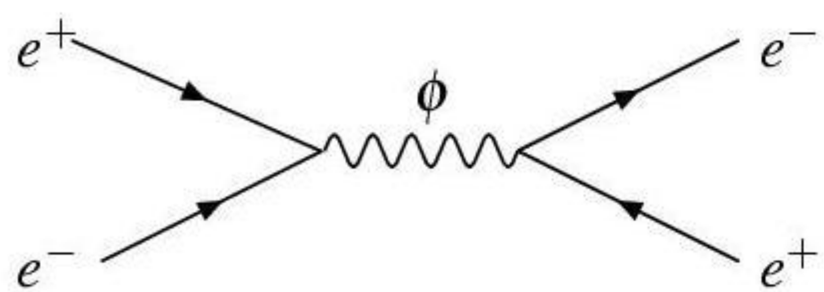
arXiv:0810.0713v2

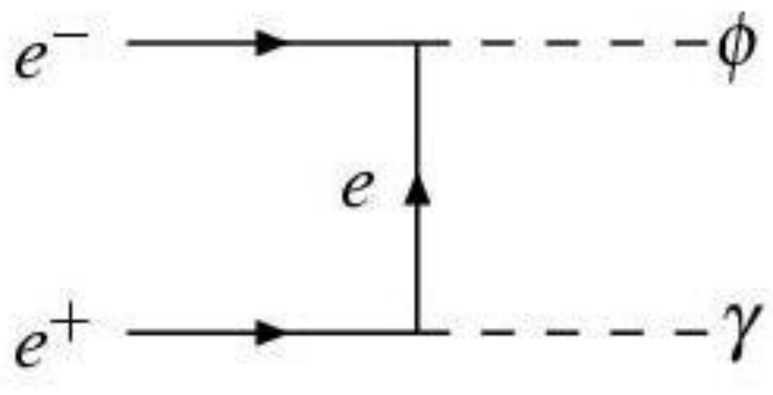
Only the LHC can produce the highest SUSY states, giving us an entry point to the dark sector through cascading and crossing-over

But why has ϕ not been observed yet?

If $\phi \rightarrow e^+e^-$, then $e^+e^- \rightarrow \phi$ is also possible

and so is $e^+e^- \rightarrow \phi\,\gamma$



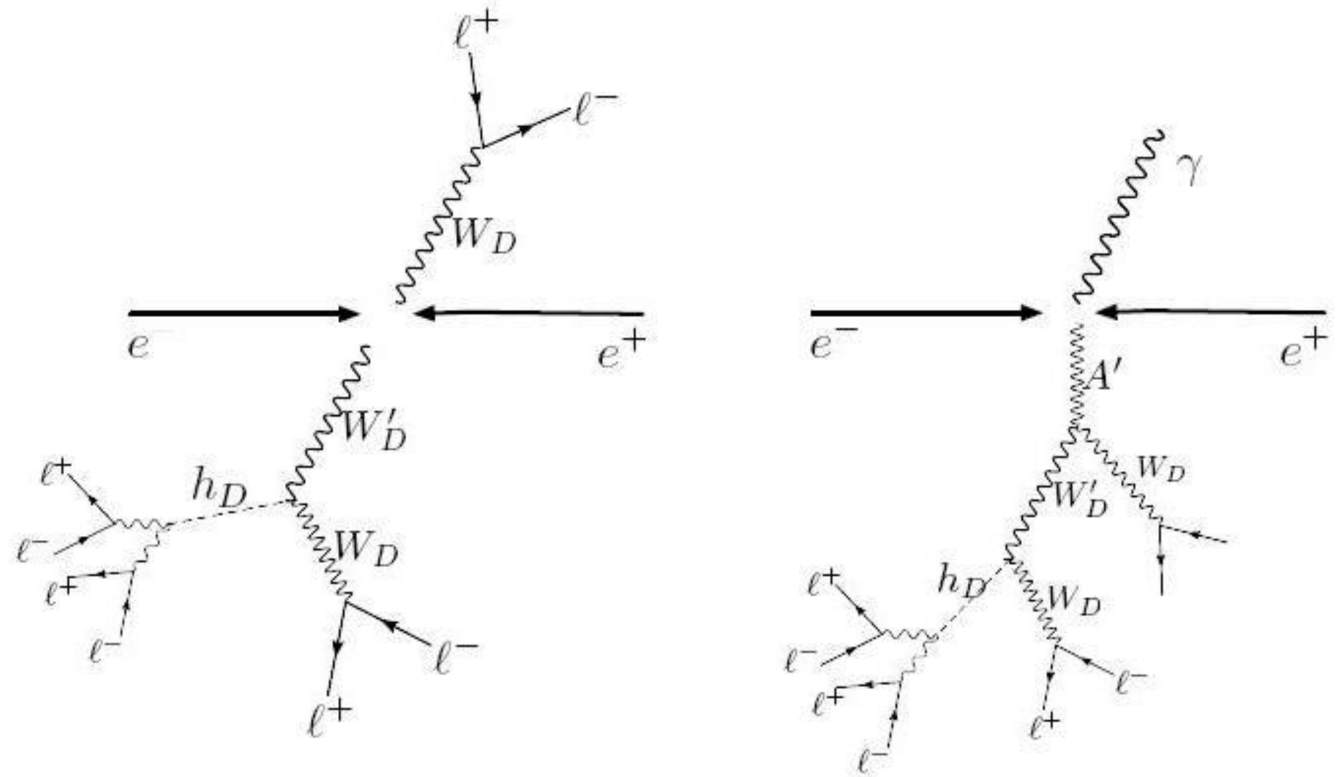


- Could look for it in Belle and BaBar data – in progress in Babar
- Resonance too narrow to be seen in a scan at low energy
- Better look for the extra photon
  - but this reduces σ by ε_{eff}^2
- A low cross-section would have prevented a discovery in earlier experiments with low energy and low luminosity

Production and decays in e^+e^- colliders

Essig, Schuster, Toro arXiv:0903.3941v1 SLAC, Stanford

Heavy dark sector gauge boson A' produced off-shell, decays into other dark sector bosons W_D then into Standard Model leptons



Signature in ATLAS: different models predict "lepton jets"

Weiner et al., Lian-Tao et al.

$\chi\,\chi \rightarrow \phi\phi$

$\phi \rightarrow e+e-$ or $\mu+\mu-$

- $m_\chi \sim$ 500-800 GeV
- $m_\phi \sim$ 100 MeV - 1 GeV

Strassler et al.

$gg \rightarrow h \rightarrow \phi\phi$

$\phi \rightarrow e+e-$ or $\mu+\mu-$

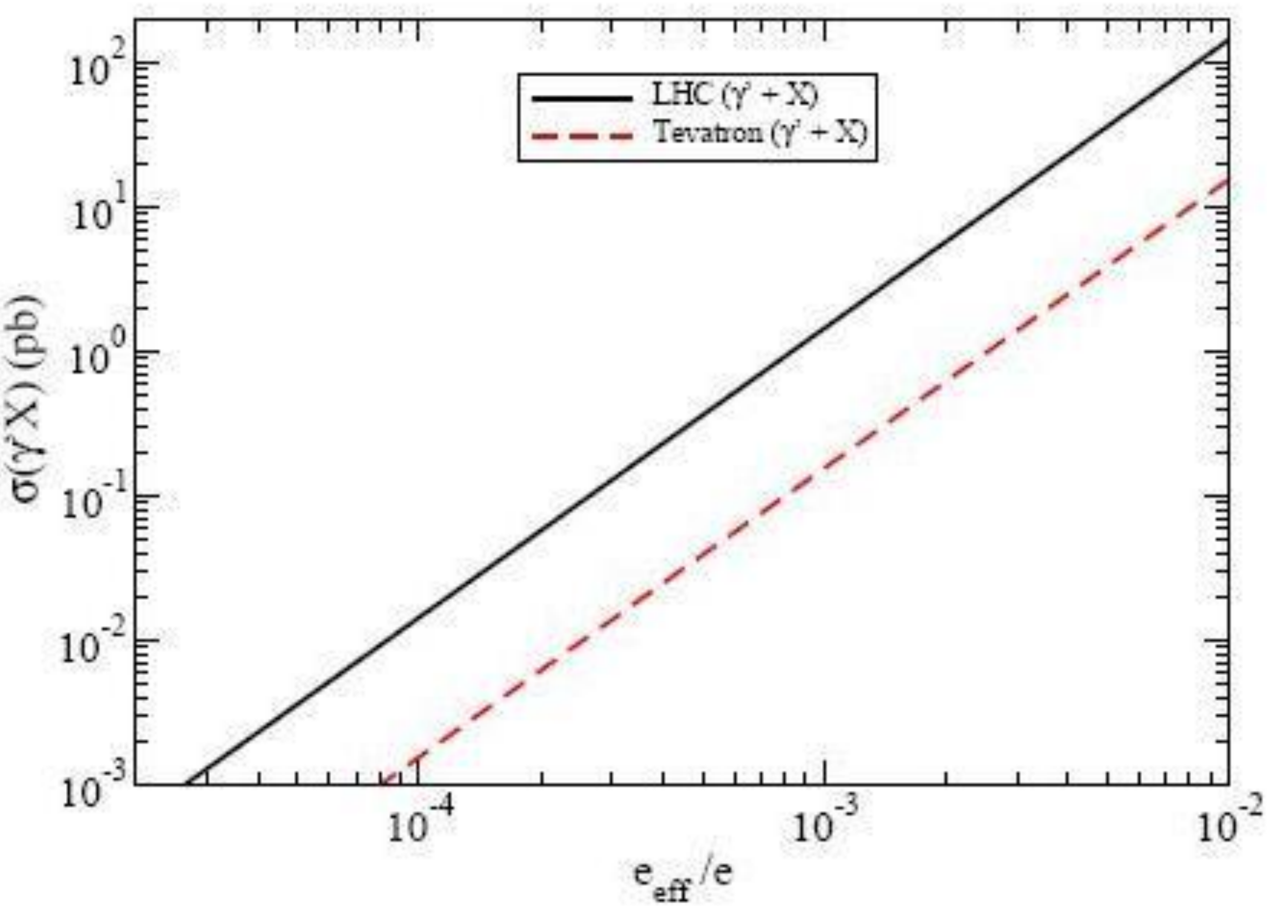
- $m_H \sim$ 140 GeV
- $m_\phi \sim$ 100 MeV - 1 GeV

- So ϕ has a large boost:
  - Very collimated or superimposed leptons
- ϕ can also be long-lived
  - would give detached vertices
  - develop new trigger algorithms
- $\phi \rightarrow e+e-$ or $\phi \rightarrow \mu+\mu-$
  - Different energy deposits could point to the same track
  - Single track would have twice the normal # of high-threshold hits in TRT
  - If overlapping, several muon segments would point to the same track or no track
  - Rejected by current trigger algorithms

Cross-section in hadron collider: could be of order 1 pb for ε ~ 10^{-3}

We expect ~200pb of data for the first year at LHC

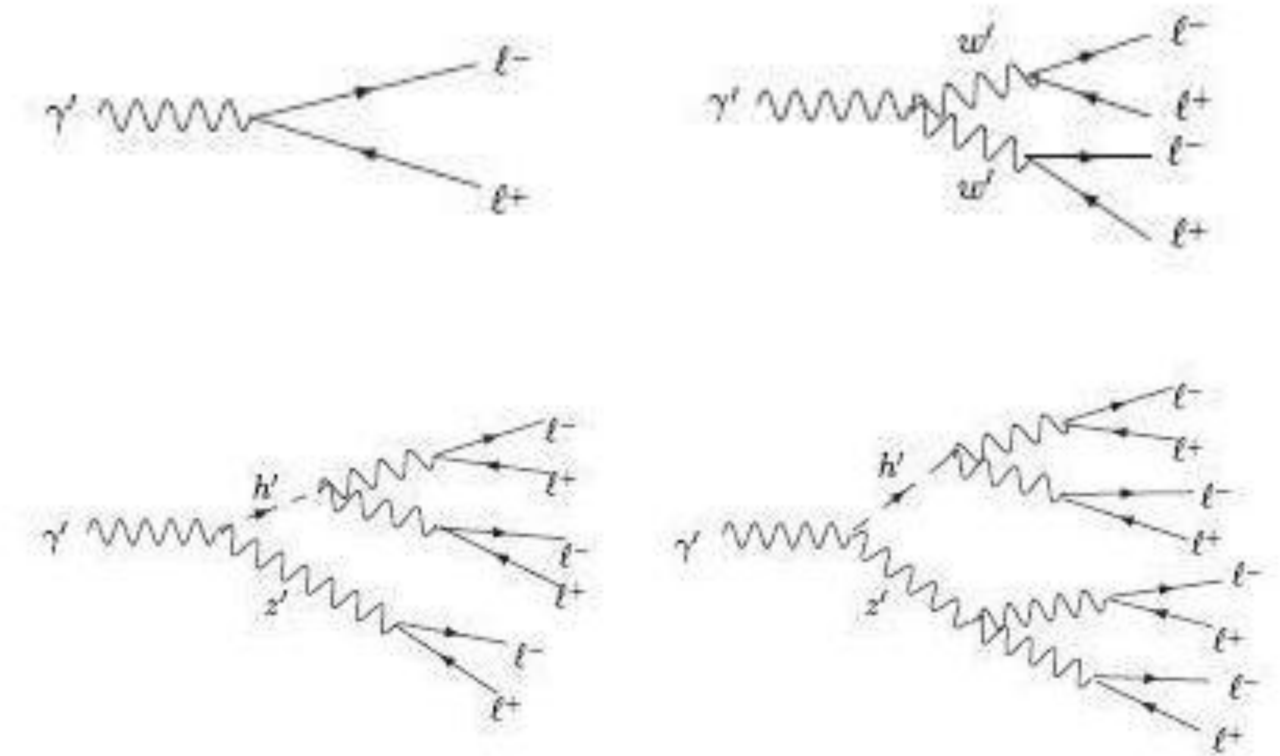
Would be visible for ε > 10^{-3}



Lian-Tao Wang et al, arXiv:0901.0283v1

Some typical dark decay chains

Lian-Tao Wang et al. arXiv:0901.0283v1

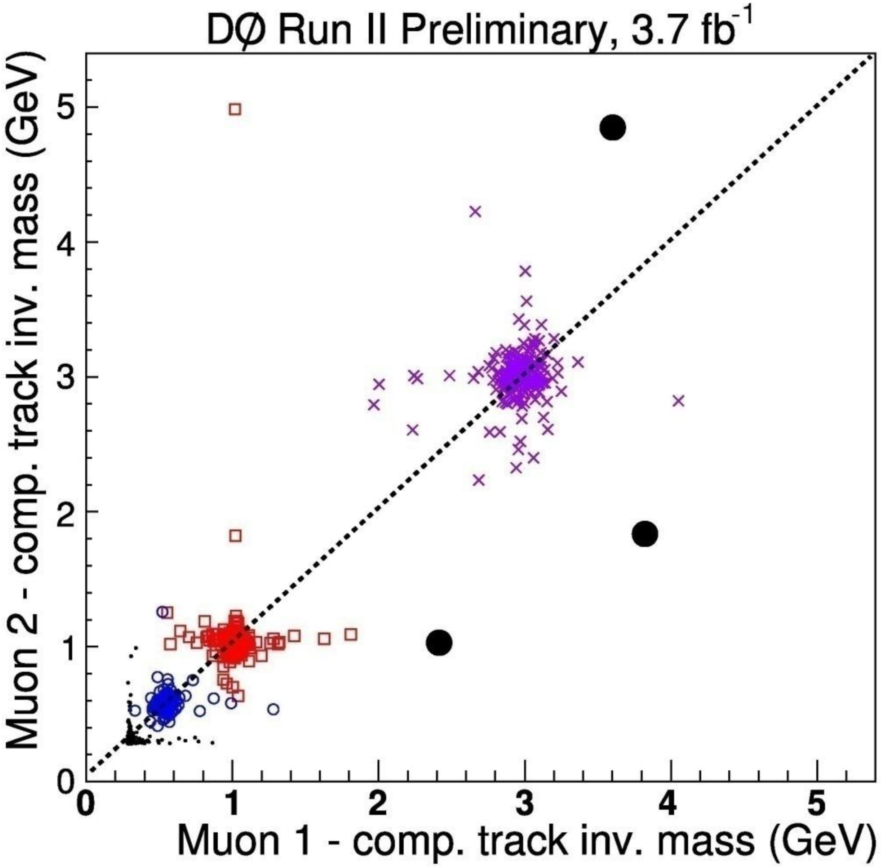


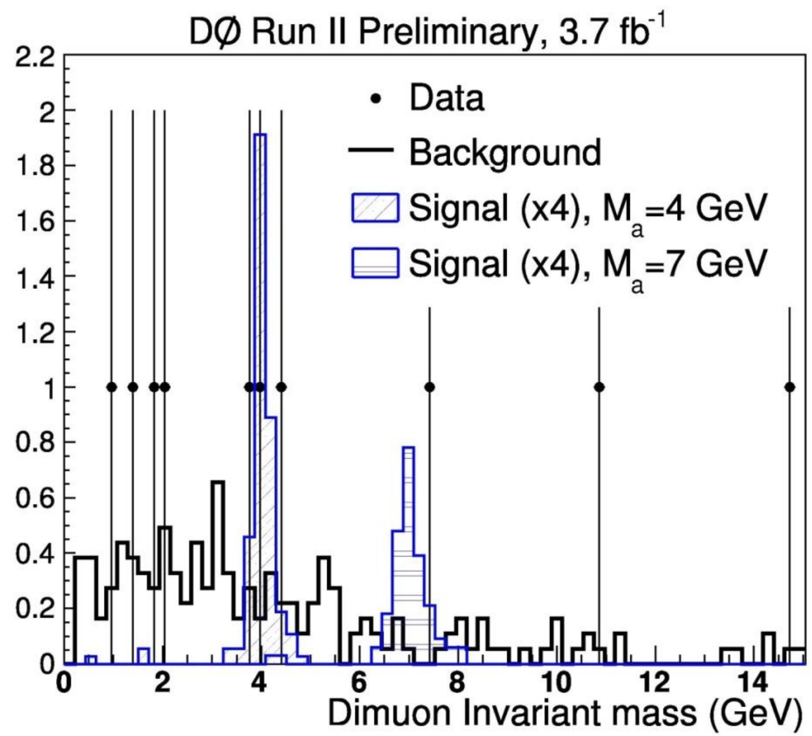
- **γ’**: dark sector gauge boson

  (ϕ in previous slides)
- Can decay directly into lepton pairs or into other dark gauge bosons **w’, z’, h’**
- Gives rise to “leptons jets” containing 2-8 leptons

NMSSM search at D0
h →aa→ μμ μμ and h →aa→ μμ ττ

Looking for two pairs of isolated muons found in a narrow cone; a muons pair is defined as one muon plus one companion track found very near the muon





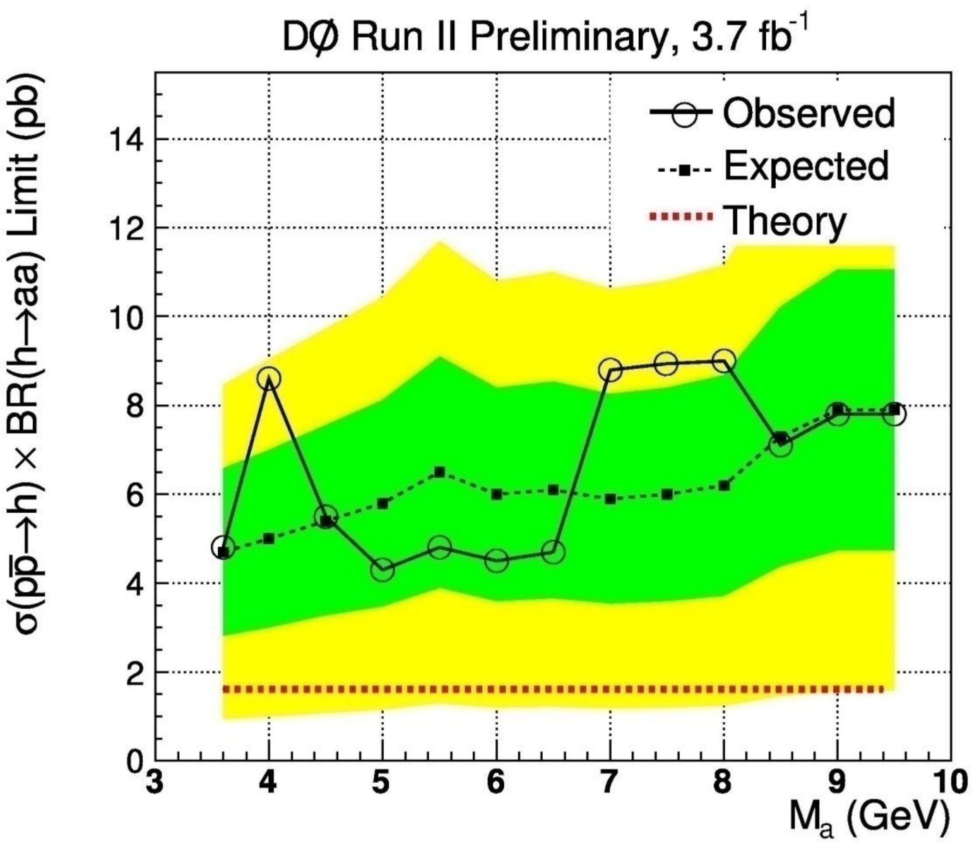
Limits on h→aa→μμ μμ from D0

- Search similar to
  h→ ϕϕ →μμ
- Look for two isolated and collimated muons
- They put a limit on

σ(pp →h+X) x BR(h→aa) x BR(a →μμ)^2 ~ 10 fb

- if σ(pp →h+X) ~ 100 fb,

then BR(a →μμ) < 10% for BR(h→aa) = 100%

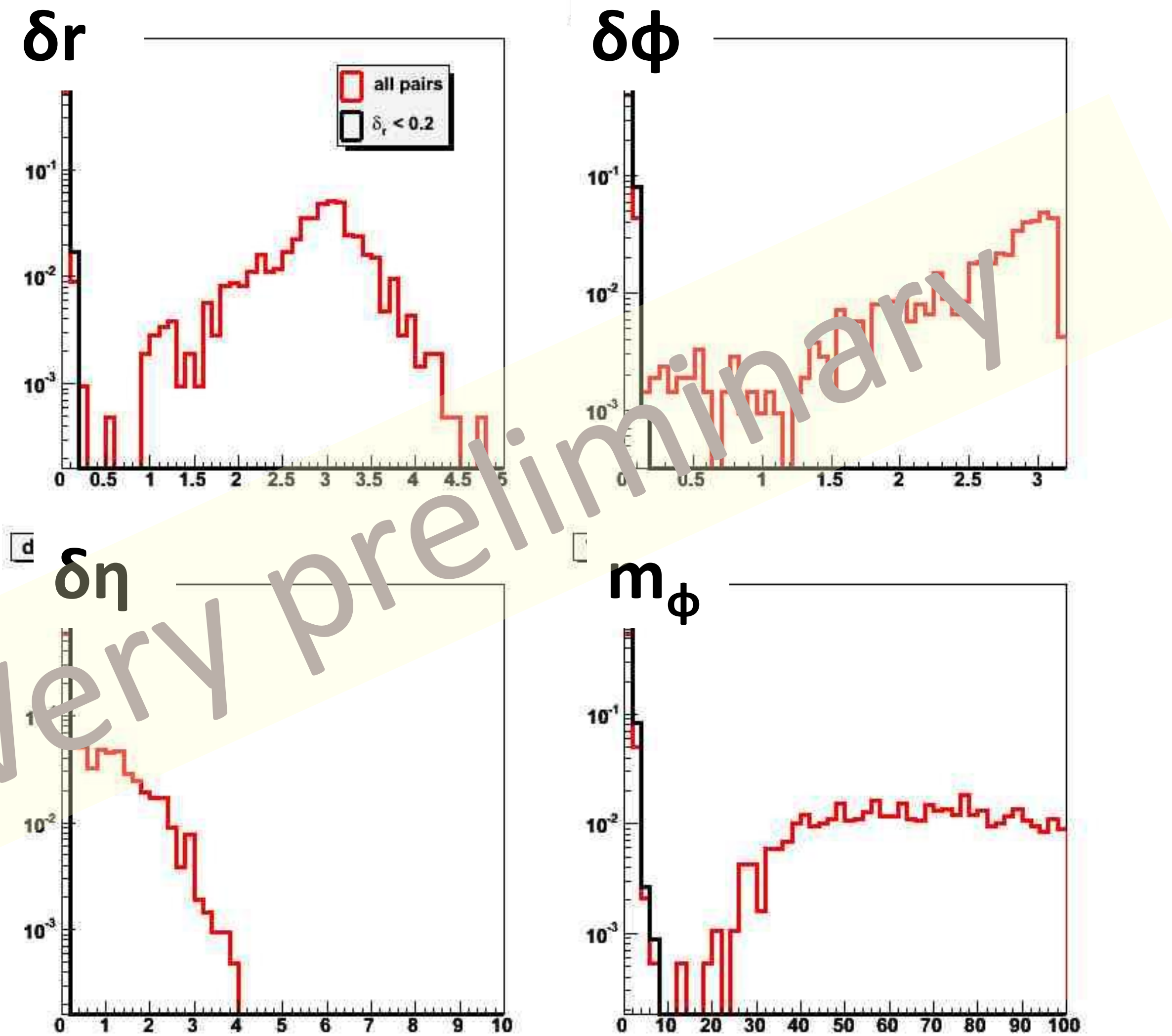


Preliminary look at lepton jets: muon pairs are found within $\delta r < 0.2$

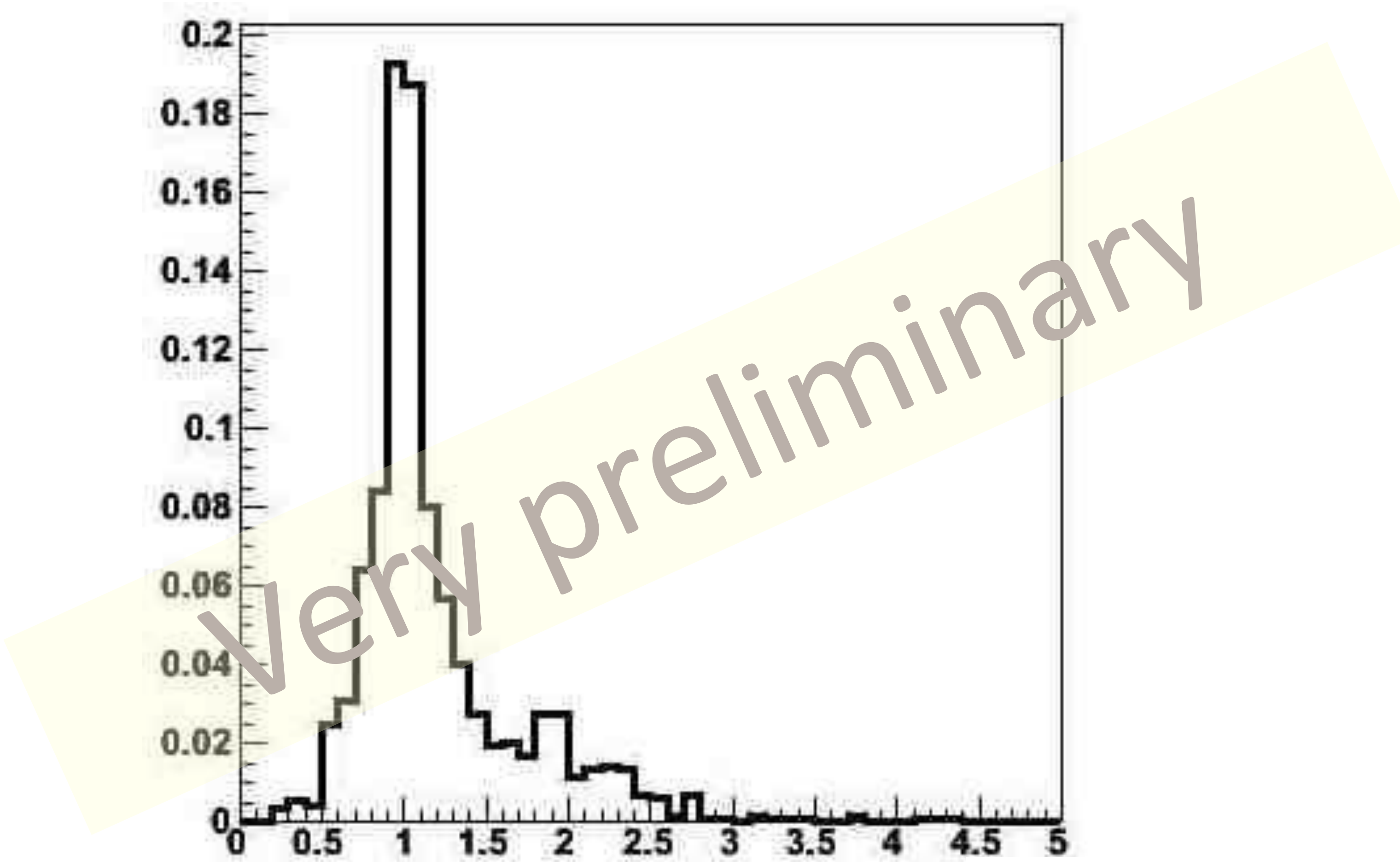
- $h \rightarrow \phi\phi \rightarrow \mu\mu\ \mu\mu$
  - Following predictions by Matt Strassler
  - $m_h = 140$ GeV
  - $m_\phi = 1$ GeV
- No problem finding μ and reconstructing ϕ
- Closest muons give the right combo:

$$\delta r < 0.2$$

$$\delta r = \sqrt{(\delta\eta^2 + \delta\phi^2)}$$



m_ϕ easily reconstructed for close muon pairs in ATLAS



m_ϕ

Main problem right now in ATLAS: trigger

- Events do not pass the ATLAS level 2 muon triggers
  - First trigger level is all hardware
  - Then level 2 and event filter are software algorithms
- Need to develop new level 2 algorithms
  - About 90% of muons pass the first trigger level
  - Only ~10% accepted when muon spectrometer segments are matched with tracks from tracking system
  - Need to develop new algorithms that won't flood the trigger system

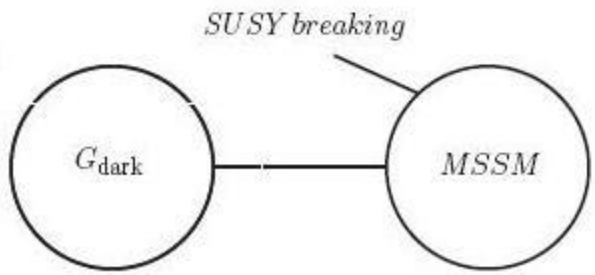
Stay tune….

- Clearly, much remains to be done on this
- For sure, interesting results will soon be available:
  - From astrophysics experiments such as Fermi
  - From the Tevatron and LHC
  - From Babar/Belle
  - From g-2 experiments
- And expect much more to be written on this topic!

But what about that moose?

Recipe for a SuperDark Moose in a Hidden Valley

- **The "Hidden Valley" bit because all this requires this parallel dark sector world called "Hidden Valley"**
- **"Super" because this one is associated with SuperSymmetry**
- **"Dark" since we're dealing with dark matter…**
- **A "moose" or "quiver" is a diagram used in gauge theory for its resemblance (!) to moose antlers…**



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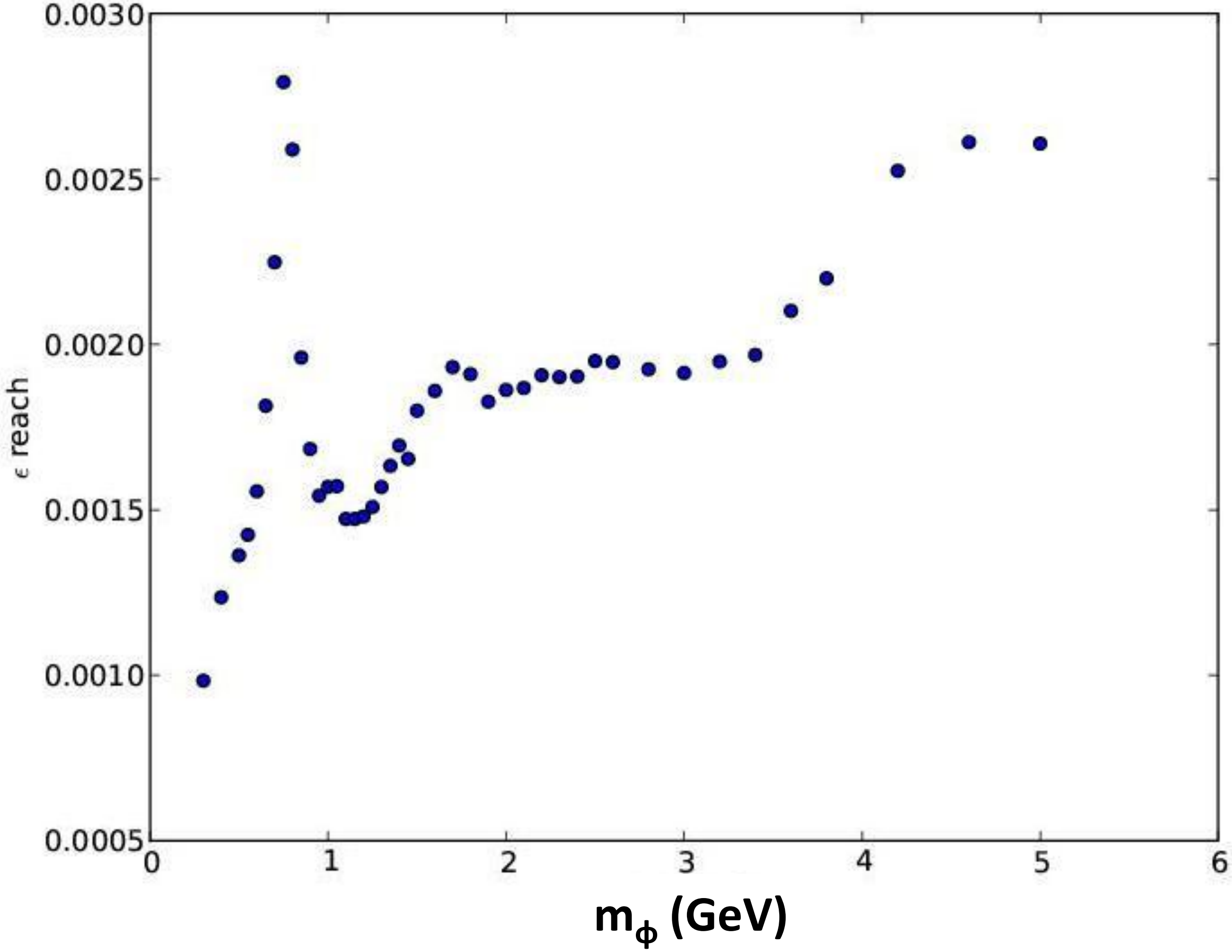
Best way to catch a moose in ATLAS

Just call it! http://www.youtube.com/watch?v=29xM6VpXWl4

Reach on ε_{eff}^2 from BaBar ~ 10^{-3}
preliminary work from Lian-Tao Wang



Decay length and track resolution

Lian-Tao Wang et al. arXiv:0901.0283v1

$$c\tau_{2-\mathrm{body}}^{\gamma'\to n\ell} \sim \frac{1}{\alpha\epsilon^2 m_{\gamma'}} = 2.7\times 10^{-6}\ \mathrm{cm}\left(\frac{\mathrm{GeV}}{m_{\gamma'}}\right)\left(\frac{10^{-3}}{\epsilon}\right)^2$$

- **With a typical boost: $\gamma \sim O(10)$, displaced vertex if $\varepsilon < 10^{-4}$**
    - **we would not see it in early data with 200 pb^{-1}**
- **The opening angle between 2 leptons is $\delta(\theta) \sim m_{\gamma'}/p_T < 0.1$**
- **This means $\Delta(\eta) \sim 50$ mrad for $\theta \sim \pi/2$**
- **ATLAS can resolve 2 tracks with about 1 mrad separation:**
    - **Pixel resolution: 100 microns; last layer at 12 cm**
    - **At higher rapidity, even easier**
- **Could be seen in early data for $\varepsilon \geq 10^{-3}$**