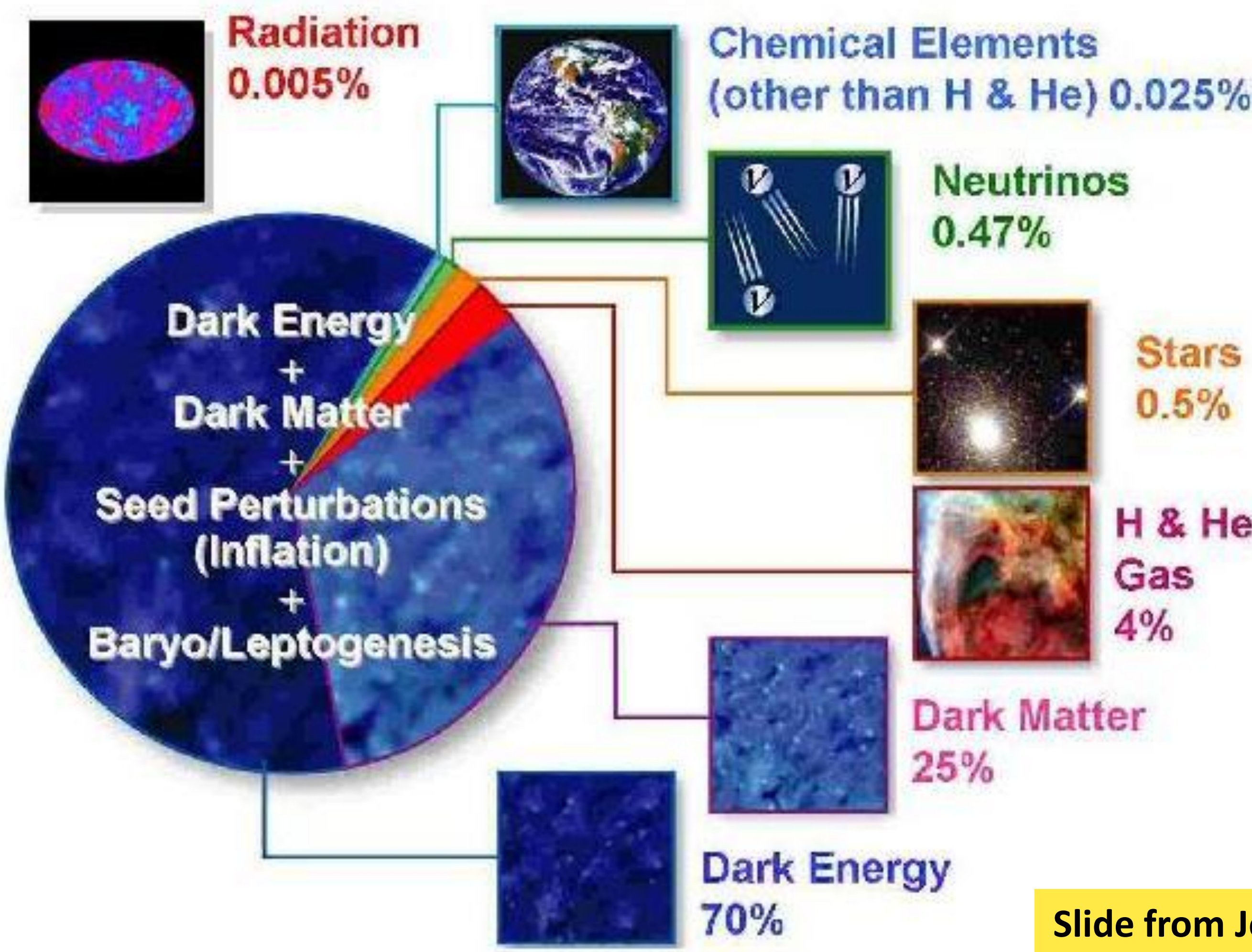
Call for a Superdark Moose in a Hidden Valley

1. Review of observed anomalies
2. Introduction to a new "Theory of Dark Matter"
3. First rough estimates and plans

Pauline Gagnon, Indiana University

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



Slide from John Ellis

What is this dark matter?

Could it explain many observed astrophysics anomalies?

Six observed, unexplained anomalies from astrophysics

High energy anomalies

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

Low energy anomalies

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

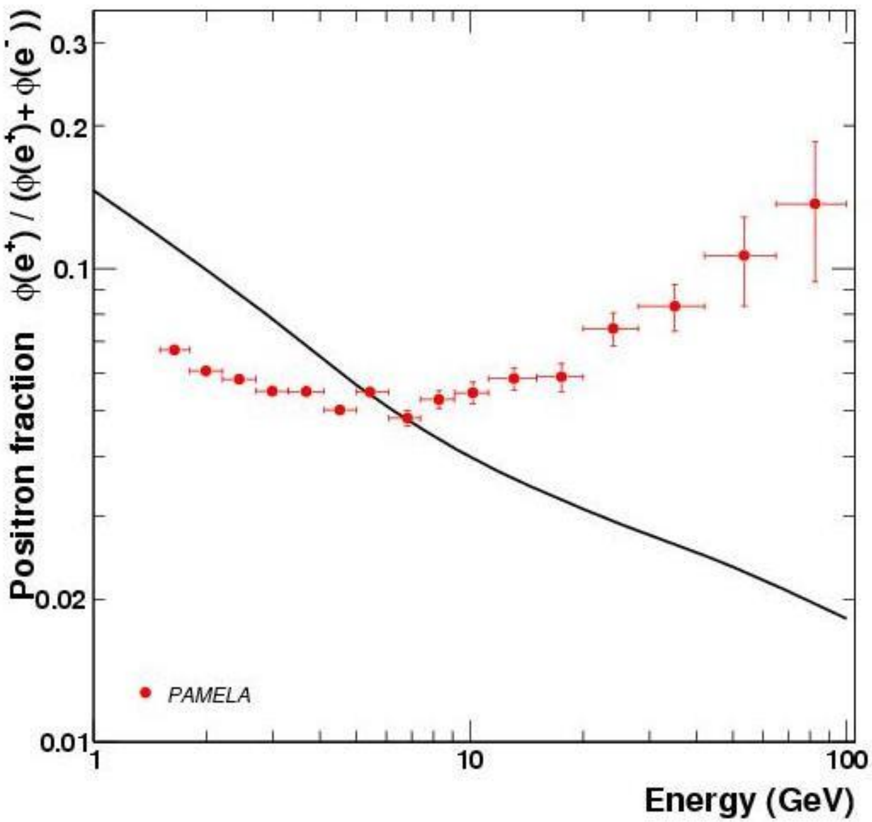


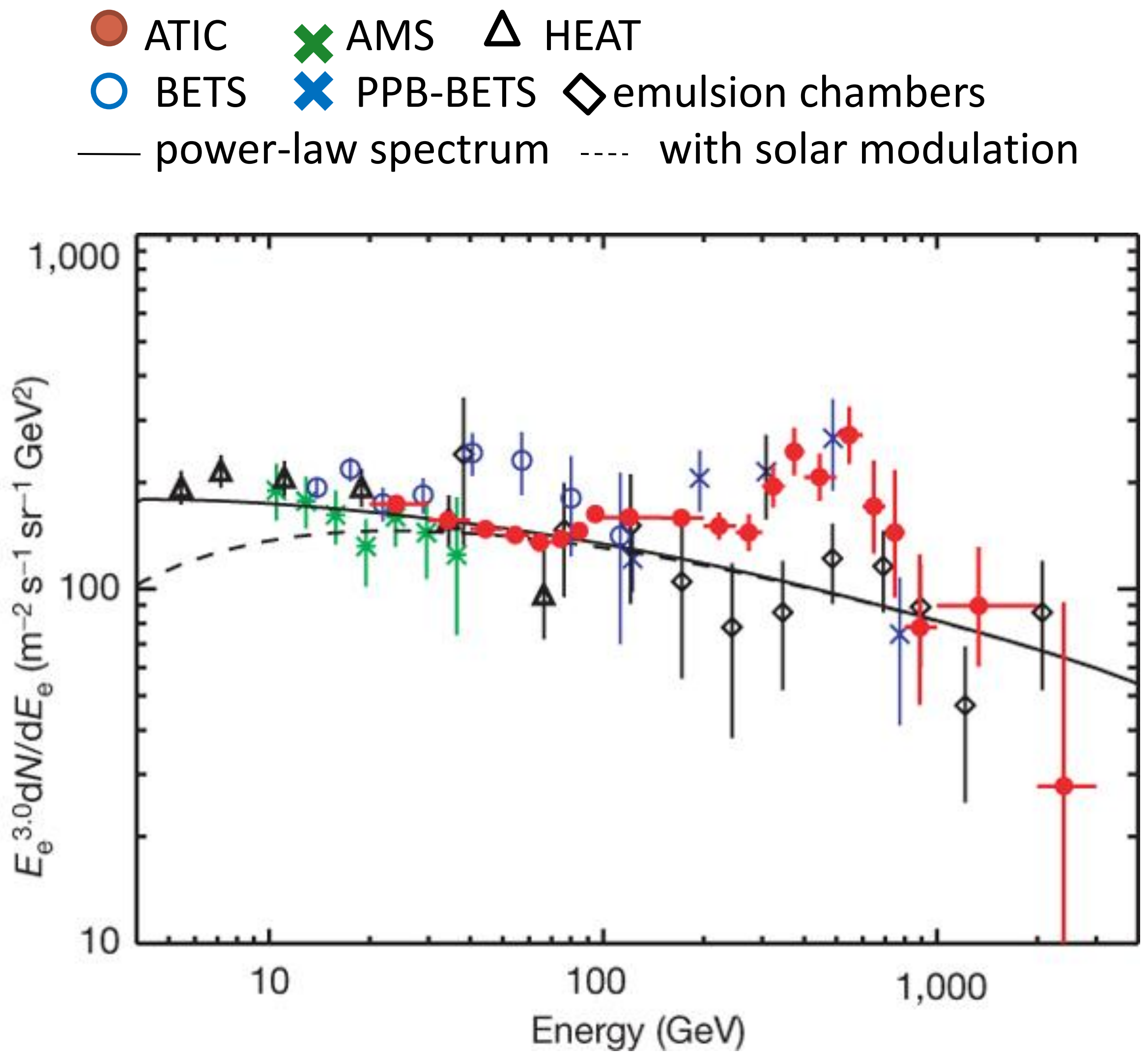
FIG. 4: **PAMELA positron fraction with theoretical models.** The PAMELA positron fraction compared with theoretical model. The solid line shows a calculation by Moskalenko & Strong[39] for pure secondary production of positrons during the propagation of cosmic-rays in the galaxy. One standard deviation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

2. The ATIC anomaly:

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

excess in cosmic ray electron flux at 300-800 GeV

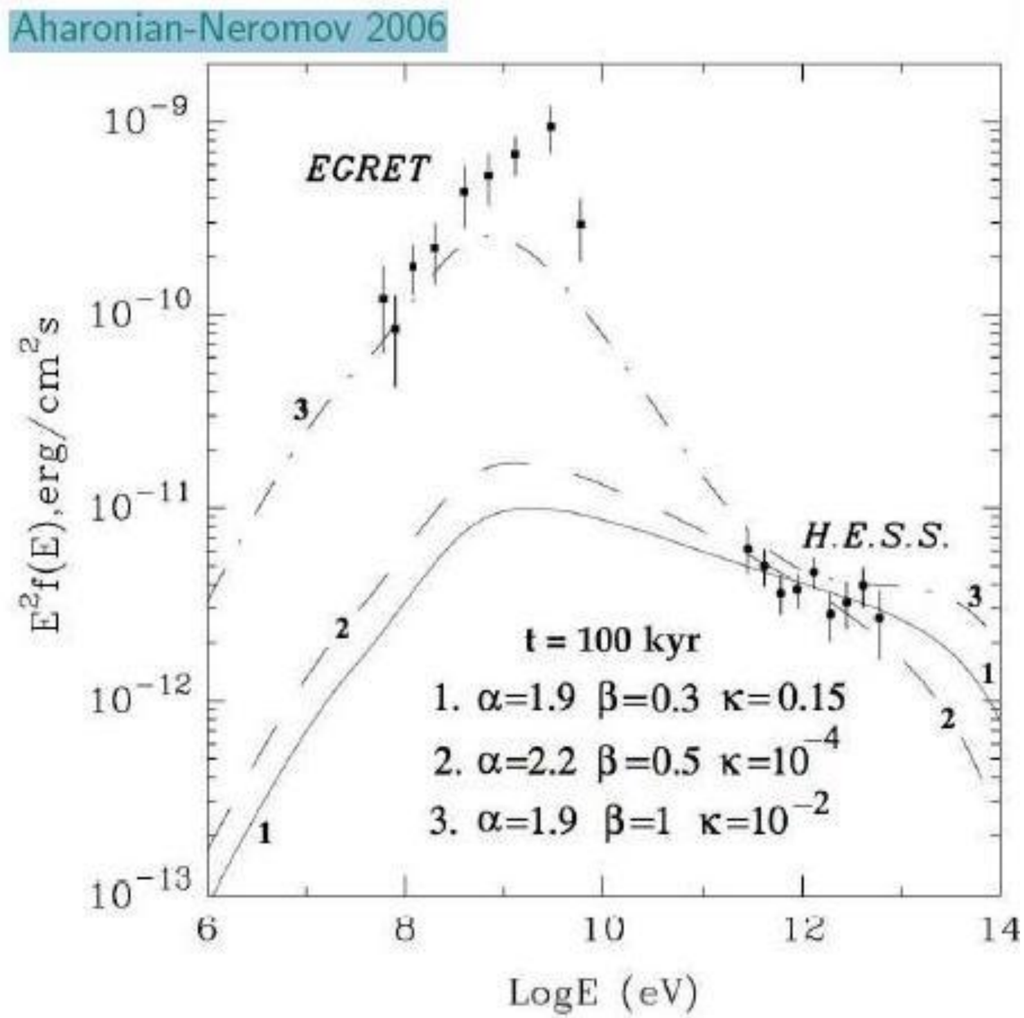
FERMI will soon release its data on high energy electron → will confirm or dismiss ATIC result (paper submitted March 20th)



Nature 456, 362-365 (2008)

3. **EGRET:**

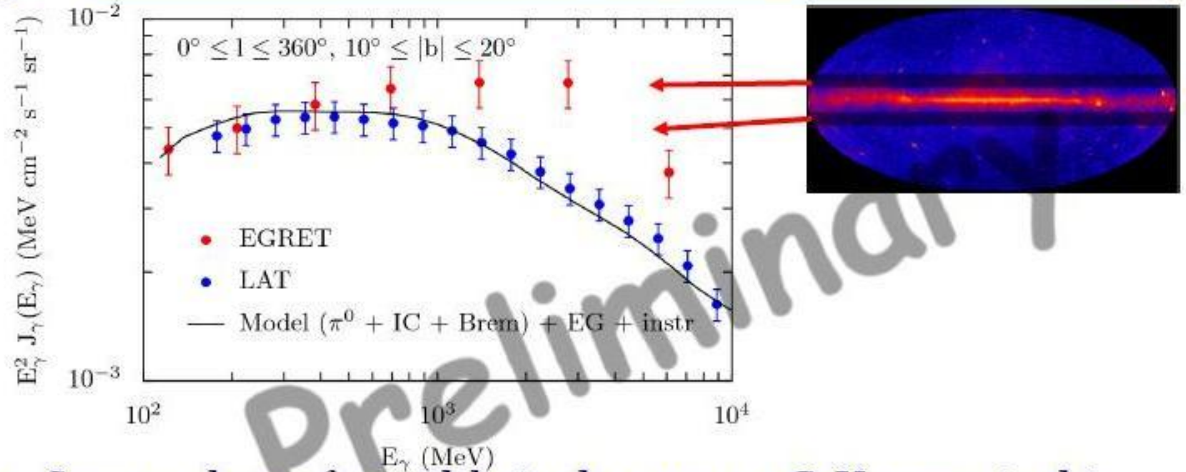
- γ-ray measurements in galactic center shows excess at 10-50 GeV
- Same amount of data will be collected by FERMI in one year of data
- FERMI will reach 25 times EGRET sensitivity
- FERMI launched June 2008 – first data reported in Moriond



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

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

(Wilkinson Microwave Anisotropy Probe)

- WMAP sees a diffuse microwave excess coming from the core of our galaxy but not 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 1983
- 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.

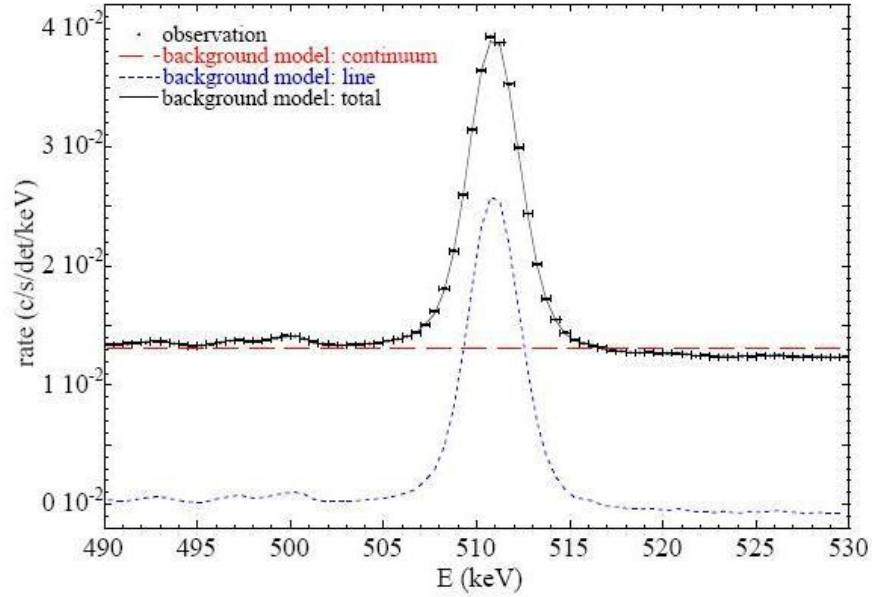
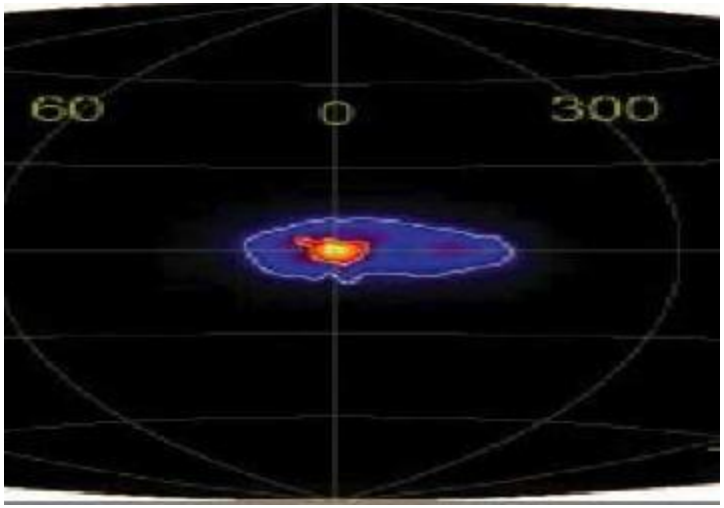


Fig. 1. Raw spectrum and background model components.

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



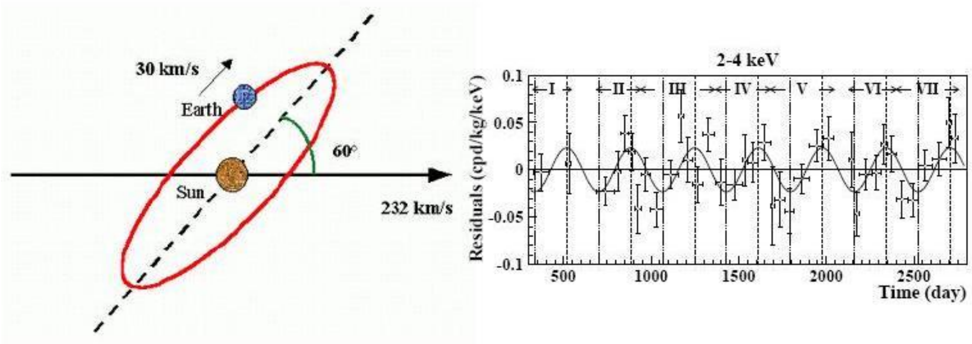
Not a symmetric source

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 and others)

Graciela Gelmini-UCLA

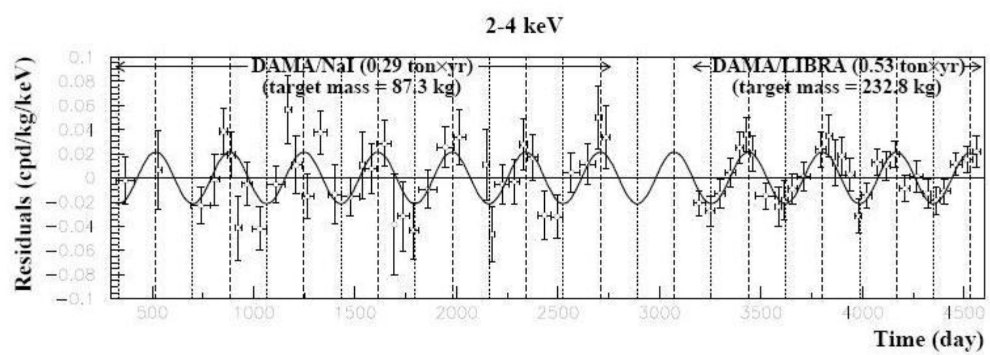
DAMA: DM signal?



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

Graciela Gelmini-UCLA

DAMA+LIBRA 11 years, 0.83 ton × year, 8.2σ modulation signal.



arXiv:0804.2741

Could these anomalies have something in common?

- Each anomaly has various alternative astrophysical explanations but they could also all have something to do with dark matter
- WMAP, (EGRET): high energy gamma ray could be due to synchrotron radiation coming from dark matter annihilation into e+ and e-
- This picture also gives rise to high energy e+ and e- to explain PAMELA and ATIC
- 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 splittings

But could one model explain them 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
  - One low mass gauge boson to address low energy phenomena

Explains both high energy and low energy anomalies

High energy:

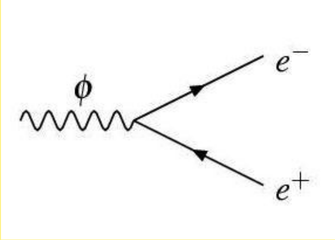
- A Weakly Interacting Massive Particle (WIMP) χ with m_χ ~ 500-800 GeV to explain high energy data
- Dark matter χ could annihilate into a light boson ϕ:

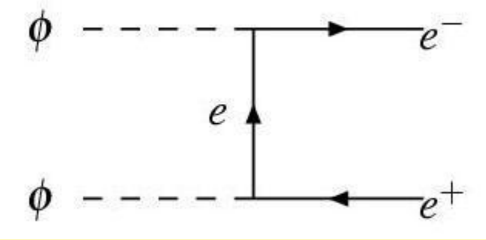
  $\chi\chi \rightarrow \phi\phi$

  $\phi \rightarrow e^+e^-$ 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, EGRET)

Low energy:

- ϕ is a new force carrier with m_ϕ ~ 100 MeV-1 GeV
- To explain INTEGRAL, need exciting dark matter (XDM)
- For DAMA data to be consistent with other null results, need inelastic dark matter (IDM)
- Both XDM and IDM can be satisfied with small mass splitting for χ
- ϕ could be so light that it can only decay into leptons

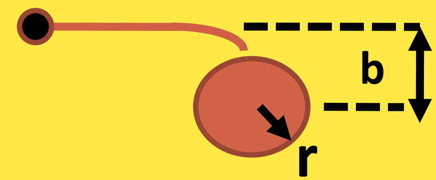




A Theory of Dark Matter

- 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 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

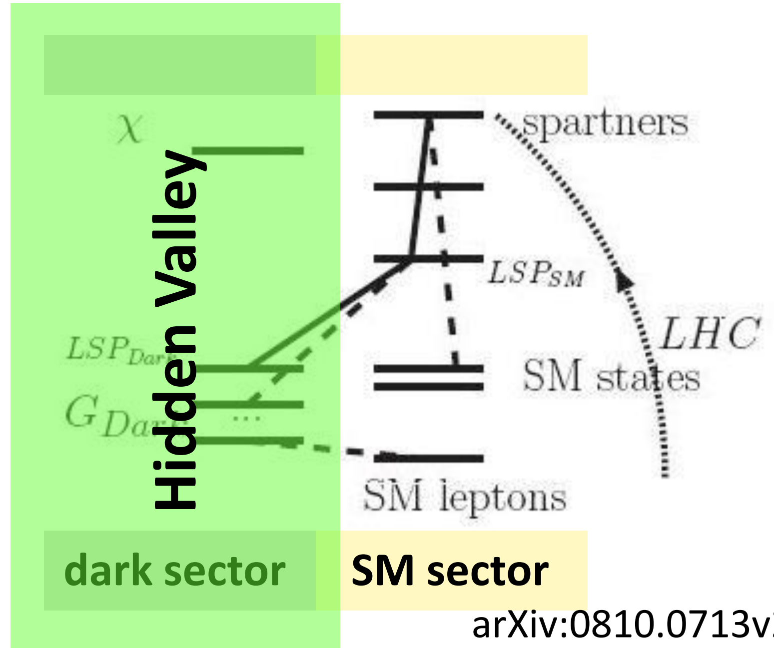
Sommerfeld enhancement:



- 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.

New picture

- Two parallel worlds:
  - SM + SUSY
  - Dark sector also with $SUSY_{dark}$
- Many χ states
- The dark matter particle χ is not the LSP (lightest supersymmetric particle)
- ϕ is the lightest state
- 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
- The LSP_{SM} is a messenger that can cross-over to the dark sector then decay into the true LSP, the LSP_{dark}
- LSP_{dark} will decay into ϕ which will decay into SM particles



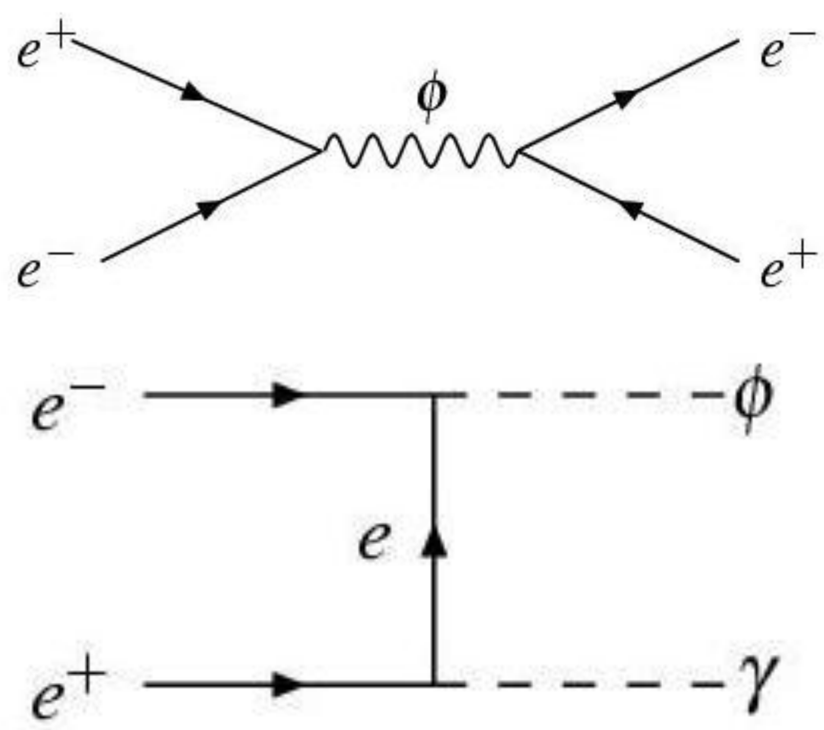
arXiv:0810.0713v2

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?

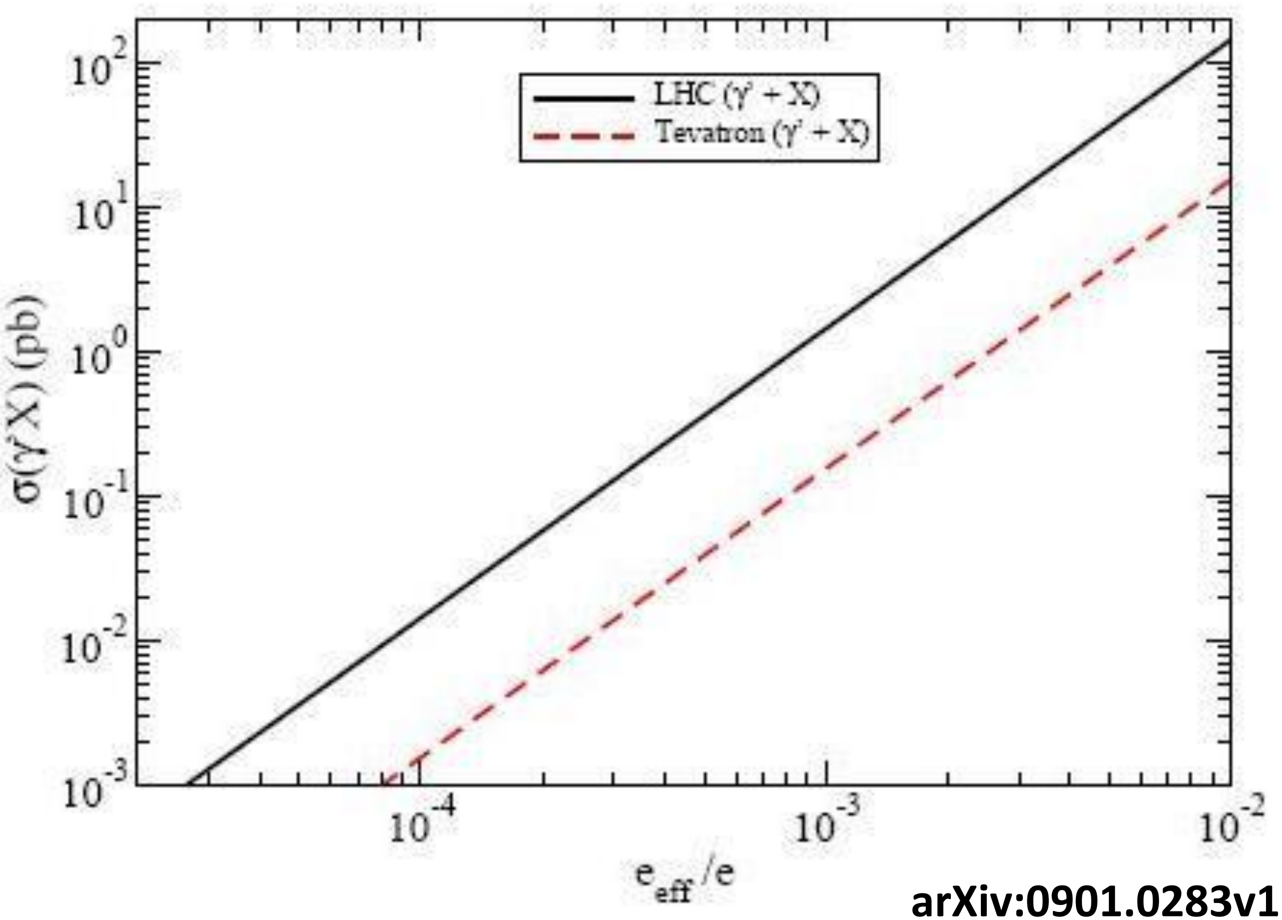
If $\phi \rightarrow e^+e^-$, then $e^+e^- \rightarrow \phi$ is also possible

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



- A new analysis is in progress in BaBar
- Resonance too narrow to be seen in a scan at low energy
- Better look for single 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

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



arXiv:0901.0283v1

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 μ+μ-

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

Strassler et al.

$gg \rightarrow H \rightarrow \phi\phi$

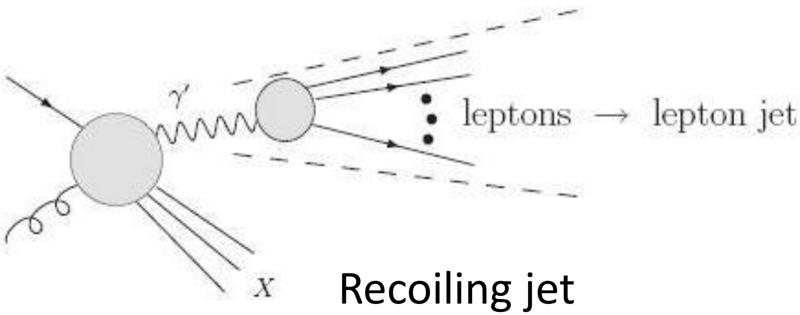
$\phi \rightarrow$ e+e- or μ+μ-

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

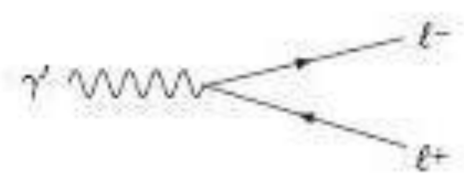
- So ϕ has a large boost:
  - Very collimated or superimposed leptons
- ϕ can also be long-lived
  - would give detached vertices
  - develop new L2 and EF triggers
- $\phi \rightarrow$ e+e-
  - Energy deposits could point to same track
  - Single track would have twice the normal # of high-threshold hits in TRT
- $\phi \rightarrow$ μ+μ-
  - If overlapping, several muon segments would point to the same track or no track
  - Rejected by MUCOMB

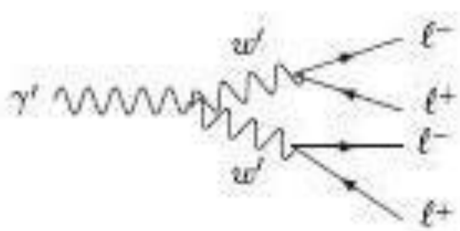
Some typical dark decay chains

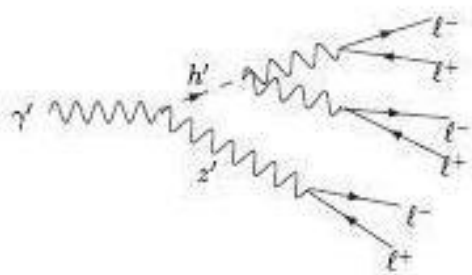
Lian-Tao Wang, Itay Yavin et al. arXiv:0901.0283v1

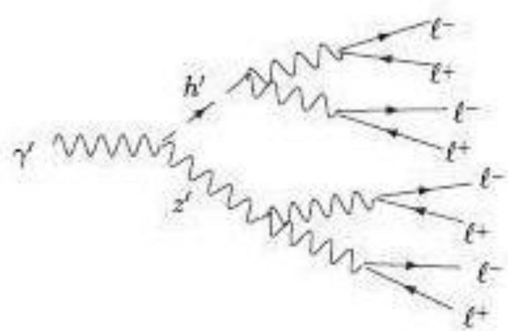


Recoiling jet









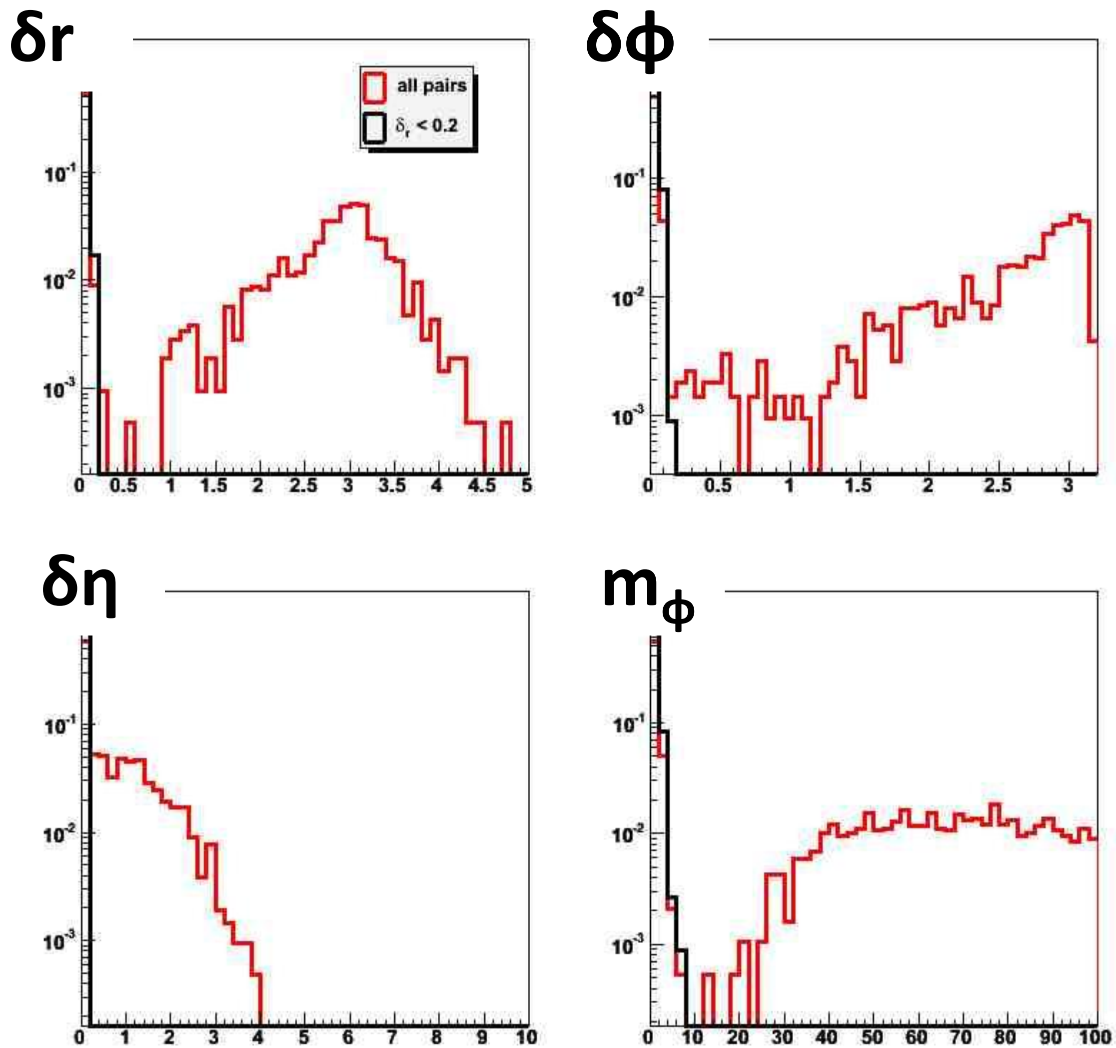
- **γ'**: dark sector gauge boson
  - **ϕ** in previous slides
- Can decay directly into lepton pairs or into other dark gauge bosons **w', z', h'**
- Gives rise to "leptons jets" containing 2-8 leptons
- **Bilge Demirkoz** is working with Itay Yavin and looking at such events
- See her talk this afternoon in the Long-Lived Particle sub-group

Preliminary look at lepton jets: muon pairs are found within δr < 0.2

- $H \to \phi\phi \to \mu\mu\ \mu\mu$
  - Produced by Daniel Ventura
  - m_H = 140 GeV
  - m_ϕ = 1 GeV
- No problem finding μ and reconstructing ϕ
- Closest muons give the right combo:

  $\delta r < 0.2$

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



Main problem right now: L2 trigger

- Events do not pass the L2 muon triggers
  - Probably rejected by MUCOMB
- Need to develop a new L2 algorithm

efficiencies	L1 w.r.t. all	L2 w.r.t. L1	EF w.r.t. L2
mu4	92.5%	14.4%	85.9%
mu6	89.7%	13.1%	88.1%
mu10	88.8%	14.7%	83.0%
mu15	86.5%	12.1%	81.4%
mu20	84.7%	9.9%	79.0%
mu40	-	4.0%	72.1%

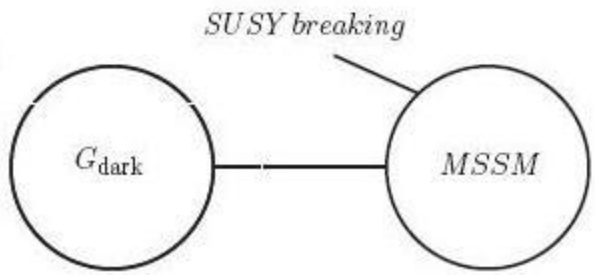
Status and Plans

- Simulate these events in ATLAS
  - Get simulation of model by Neal Weiner et al.
    - Lian-Tao Wang and Georges Azuelos (MC for Exotic group) are working on how to integrate their code within Athena
    - Bilge Demirkoz has a working version from Itay Yavin
  - University of Washington group has implemented Matt Strassler's model for Higgs v-pion to lepton jets
- Both models will be checked to see how we need to modify lepton triggers for short and long-lived particles
  - Muons pass the L1 trigger in second model
- Develop a selection analysis for the early data

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…**



? =