Title: Dark Matter: New Data and New Dynamics?

Date: Feb 02, 2010 02:00 PM

URL: http://pirsa.org/10020033

Abstract: The quest to understand the nature of dark matter is entering a remarkable data-rich era. Hypothetical stable, electrically neutral particles with TeV-scale mass and weak-strength couplings are a simple, theoretically appealing, but untested candidate for the dark matter. I will summarize recent results in both direct and indirect searches for dark matter, and highlight what upcoming data may teach us. I will also discuss the key role of accelerator-based experiments and novel astrophysical measurements in understanding dark matter and its connection to Standard Model physics. The prospects are particularly rich if dark matter interacts through new, non-Standard-Model dynamics, as recent cosmic-ray data may suggest. I will discuss a range of collider-based searches and fixed-target experiments under development to search for this dynamics, and the complementary sensitivity of searches for cosmic rays originating from dark matter annihilation in the sun.

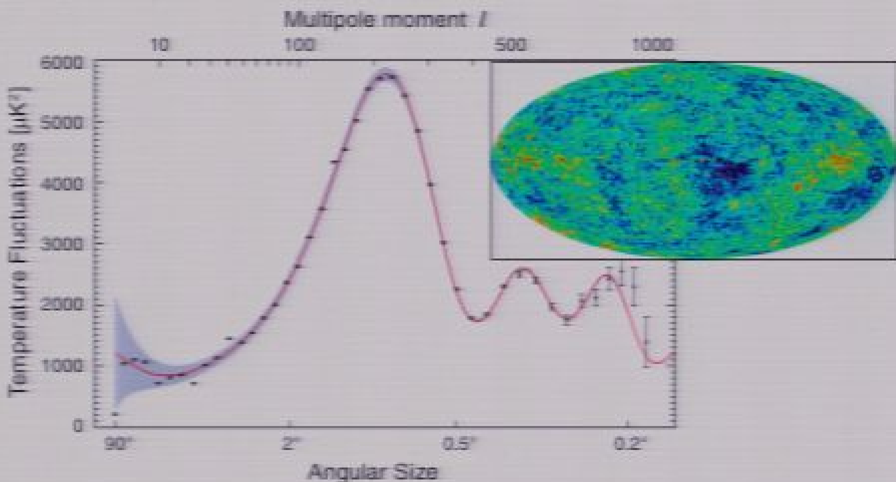
Dark Matter:
New Data, New Dynamics?

Natalia Toro

Stanford University

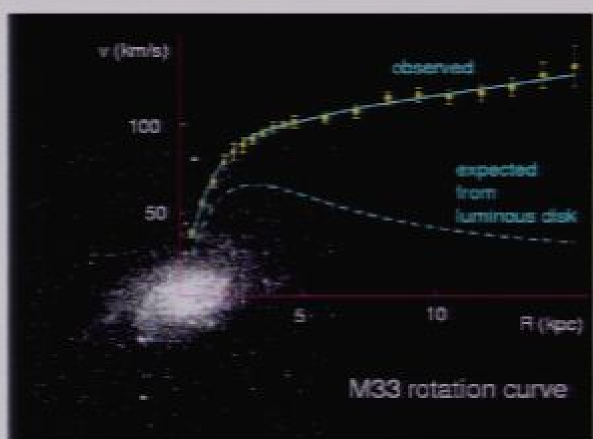
Evidence for dark matter

Cosmological Data:



Dark matter is **cold** (non-relativistic at recombination), **non-baryonic**, and comprises ~23% of critical density

Galactic Data and Simulations



Local density and velocity:

$$\rho \approx 0.3 \text{ GeV}/\text{cm}^3$$
$$\bar{v} \approx v_\odot \approx 250 \text{ km/s} \ \ (10^{-3}c)$$

~10x more dark matter at galactic center *(considerable uncertainty)*

Weak lensing and stellar velocity measurements probe dark matter in other galaxies

Beyond Gravity

- Does dark matter have non-gravitational interactions?
- What dynamics determines its density?

  Particle physics motivates many candidates:
  - Weakly Interacting Massive Particle (m~TeV, electromagnetically neutral, but O(1) couplings to some other massive particles): cooling of a hot universe leaves residual density.
  - Axion, ...
- Origin of dark matter is a window on early cosmology
- Dark matter interactions may help resolve other mysteries of fundamental physics (e.g. CP symmetry in strong interactions, electroweak hierarchy, supersymmetry)

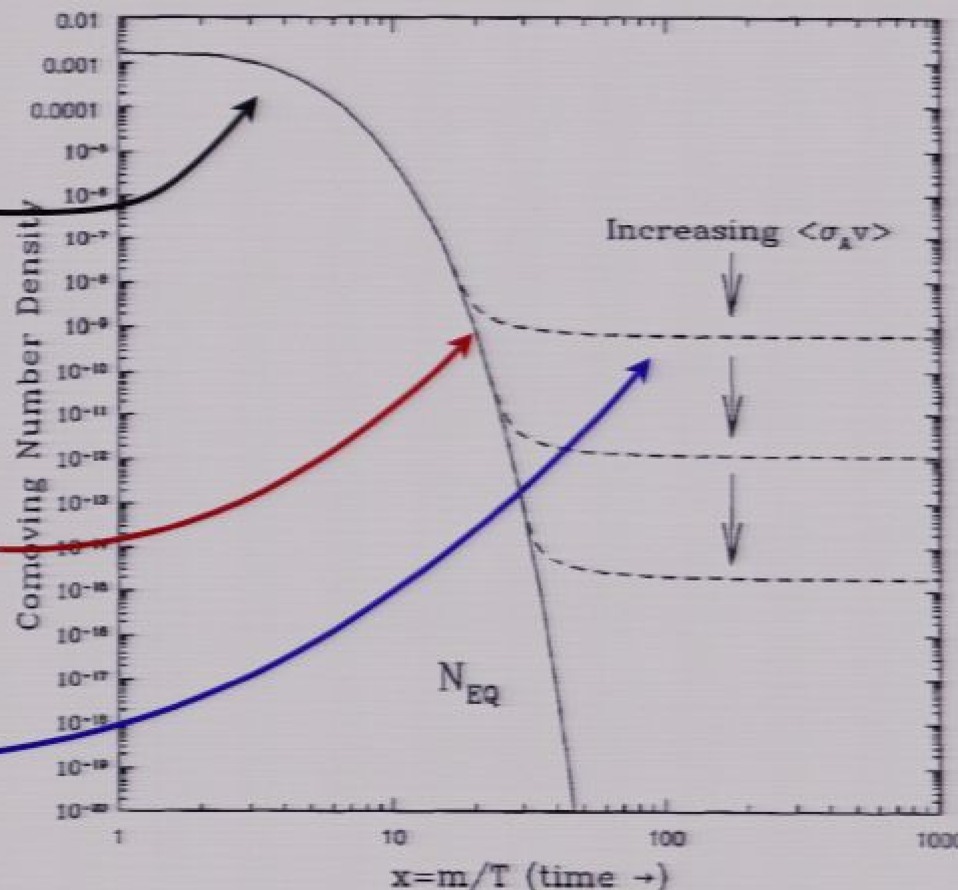
The Origin of WIMP Dark Matter

For $T \gtrsim M_\chi$, dark matter is in thermal equilibrium:

$$n = T^3 e^{-m/T}$$

When $n\langle\sigma v\rangle \lesssim 3H$, dark matter annihilation becomes ineffective
$\Rightarrow$ thermal equilibrium is lost

After freeze-out, density per comoving volume is fixed.
Determines $\langle\sigma v\rangle$



Typical annihilation cross-section $\langle\sigma v\rangle \sim \dfrac{\alpha^2}{M_\chi^2}$

$\Rightarrow$ e.g. weak interactions: $\alpha_w^2 \approx 10^{-3}$ & $M_\chi \sim$ TeV

The Next Few Years in Dark Matter: Overview

1. Dark Matter Scattering (DAMA, XENON 10, CDMS, CRESST… XENON 100, LUX)

2. Dark Matter Annihilation (PAMELA, ATIC, Fermi, HESS… AMS-II)

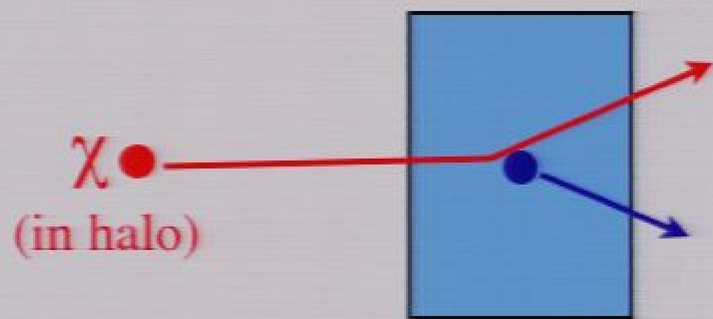
   *Hints of physics **far** beyond the Standard Model*
   in particular: a new force, mediated by a GeV-mass gauge boson

3. Dark Matter Dynamics: Accelerators and Exotic Astrophysical Signals (BaBar, Belle, KLOE, small-scale fixed-target experiments, Fermi again!)

   Looking for new physics in non-standard places

Only by probing all facets of new physics associated with dark matter can we identify its nature & implications.

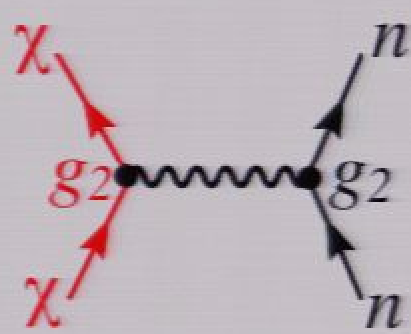
Direct Detection: Nuclear Scattering



Rate proportional to reduced mass $\mu(\chi, \text{Target})$
$\Rightarrow$ highest for targets of mass near dark matter mass (nuclei)

Bigger, lower-background experiment → Probe weaker interactions with matter

e.g. Z-mediated:



$$\sigma_n \sim \frac{\alpha_2^2 \mu_n^2}{m_Z^4} \sim 10^{-38}\ \text{cm}^2$$

XENON 100: Direct Search State-of-the-Art

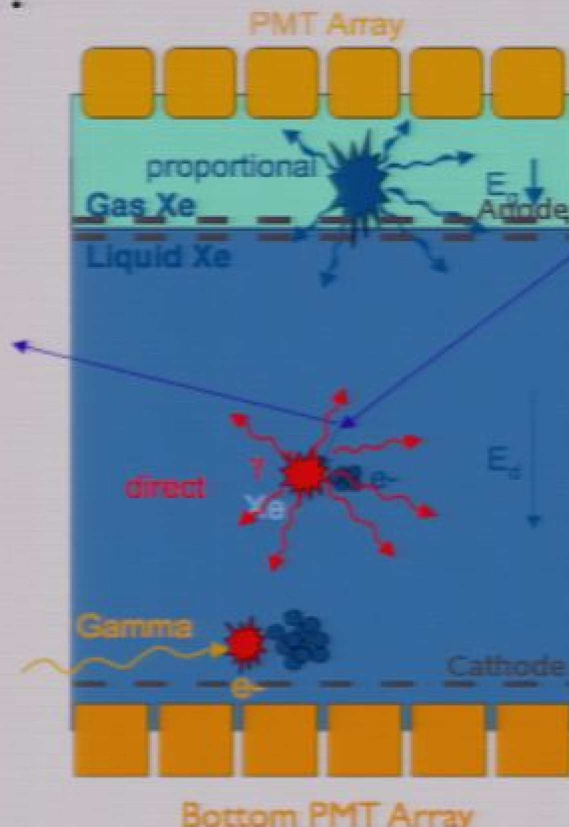
Large mass ⇒ high WIMP event rate.

50-kg Xe detector, 1 TeV WIMP:

$$\left(\frac{\sigma}{10^{-44}\,\mathrm{cm}^2}\right) \times 1/\mathrm{day}$$

Very clean:
- reject e^- recoils
- reject surface events

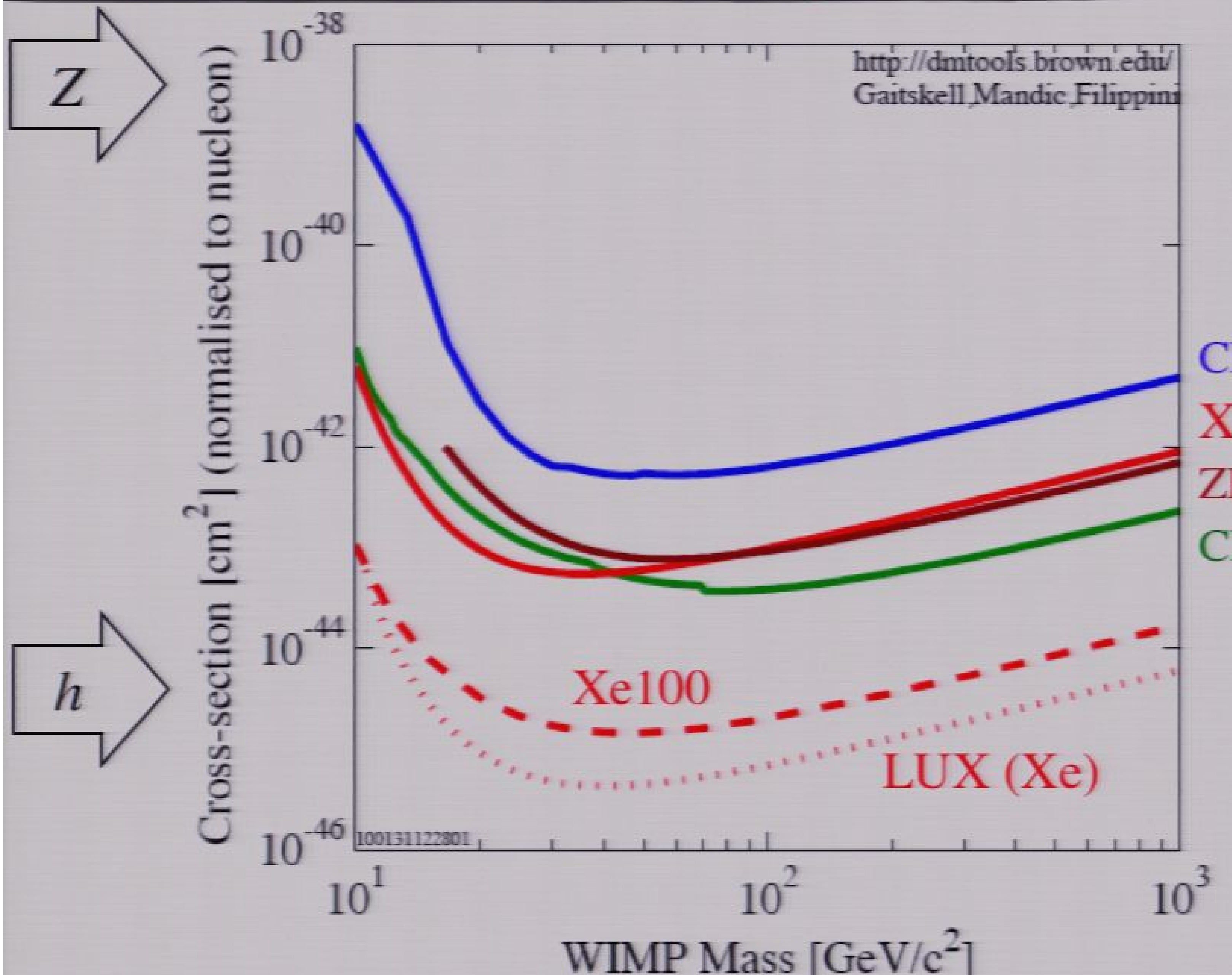
Taking data since Dec;
first results this spring.



[talk by
M. Schumann]

(LUX very similar, online later 2010 at Homestake)

Current and Future Sensitivity



1Ton LUX/ ZEPLIN: Another factor of 50 by 2013?

Current sensitivity ~ 10^{-42} cm^2 — no Z interaction?

Z-Mediated Scattering, reconsidered

Massive spin-1 fields mediate <u>typically off-diagonal</u> interactions:

e.g. Complex scalar field $\varphi = \phi_1 + i\phi_2$

Gauge interaction $D_\mu \varphi^* D^\mu \varphi \to q A^\mu (\phi_1 \partial_\mu \phi_2 - \phi_2 \partial_\mu \phi_1)$

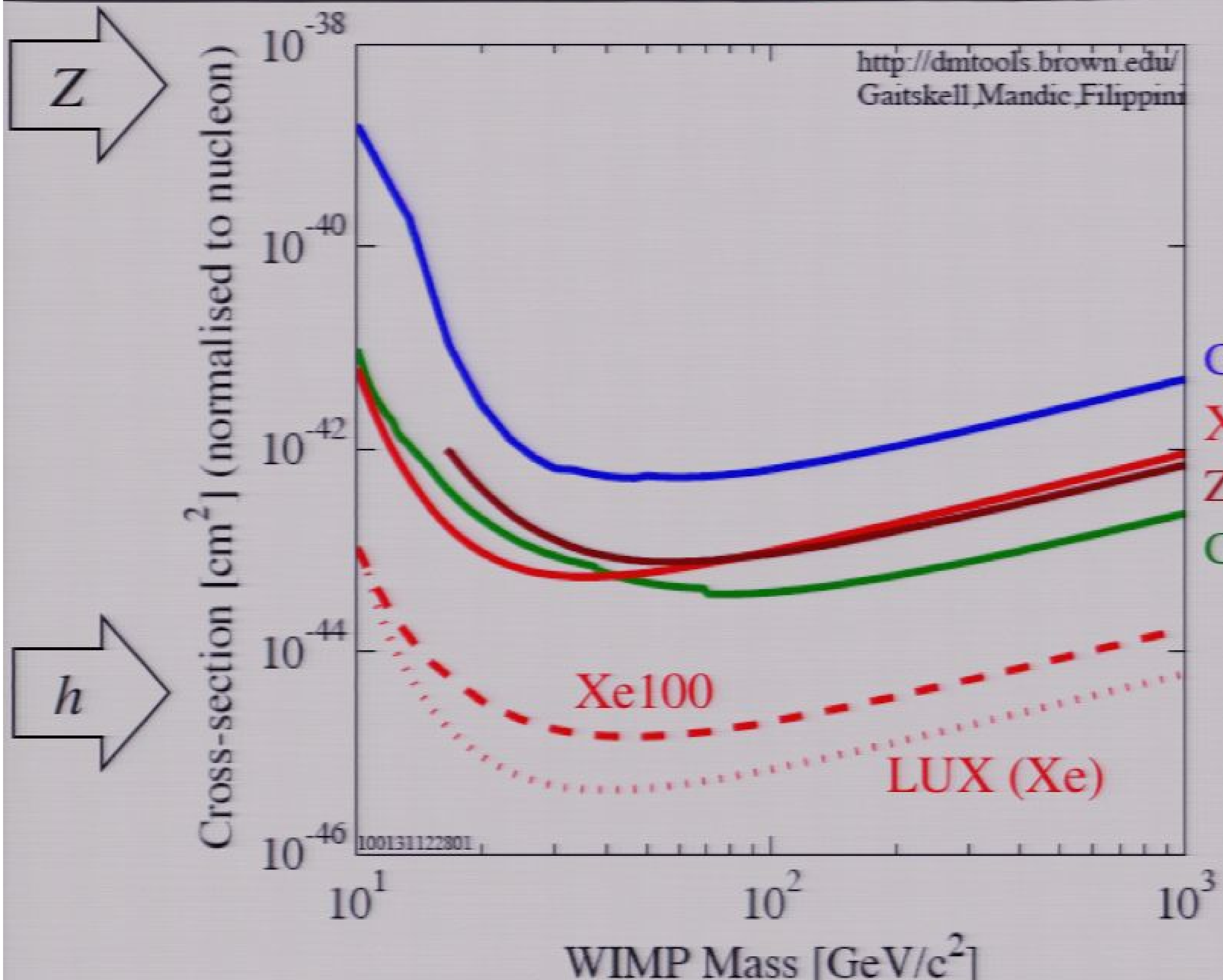
Most general mass matrix splits ϕ_1 and ϕ_2

Standard Model: *W* couplings *are* mass off-diagonal; splittings in *Z* exchange forbidden by $U(1)_{EM}$.

⇒Inelastic dark matter scattering

Null result ⇒ no *Z* coupling **OR** large splitting (and χ* unstable)

Current and Future Sensitivity



1Ton LUX/ ZEPLIN: Another factor of 50 by 2013?

Current sensitivity ~ 10^{-42} cm^2 — no Z interaction?

Z-Mediated Scattering, reconsidered

Massive spin-1 fields mediate typically off-diagonal interactions:

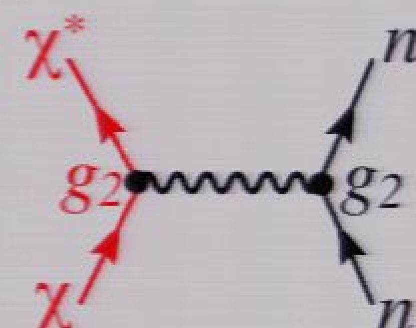
e.g. Complex scalar field $\varphi = \phi_1 + i\phi_2$

Gauge interaction $D_\mu \varphi^* D^\mu \varphi \to q A^\mu (\phi_1 \partial_\mu \phi_2 - \phi_2 \partial_\mu \phi_1)$

Most general mass matrix splits ϕ_1 and ϕ_2

Standard Model: *W* couplings *are* mass off-diagonal; splittings in *Z* exchange forbidden by $U(1)_{EM}$.

⇒Inelastic dark matter scattering

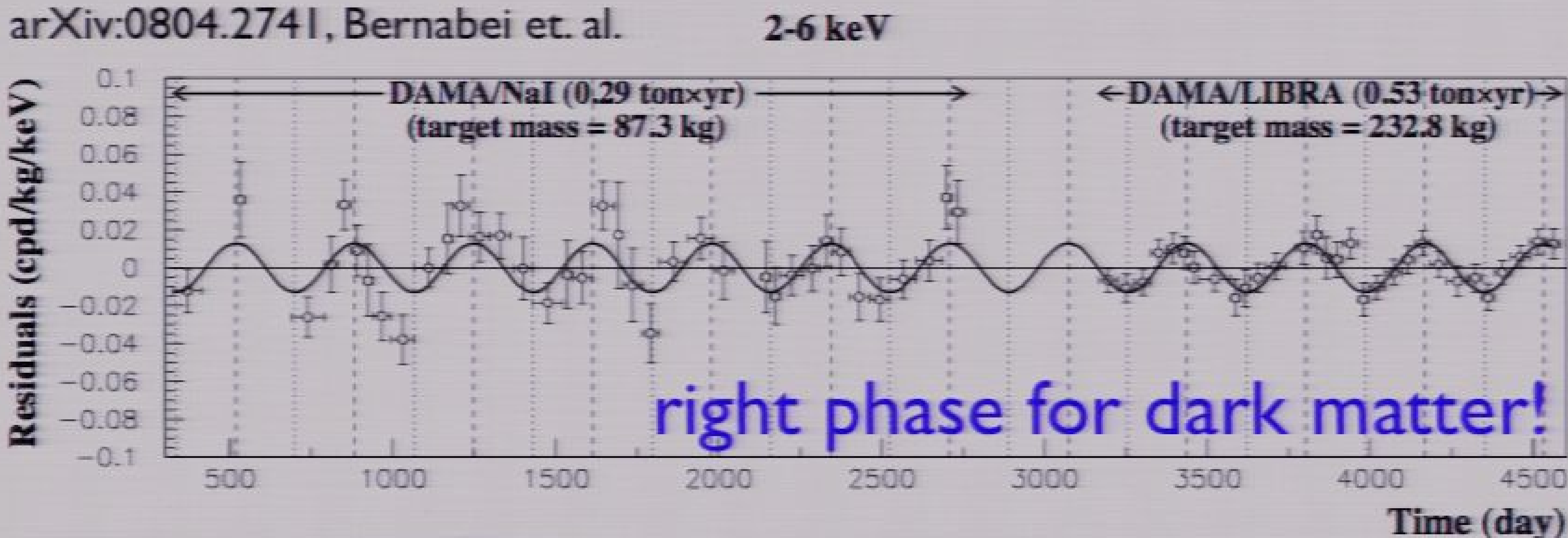


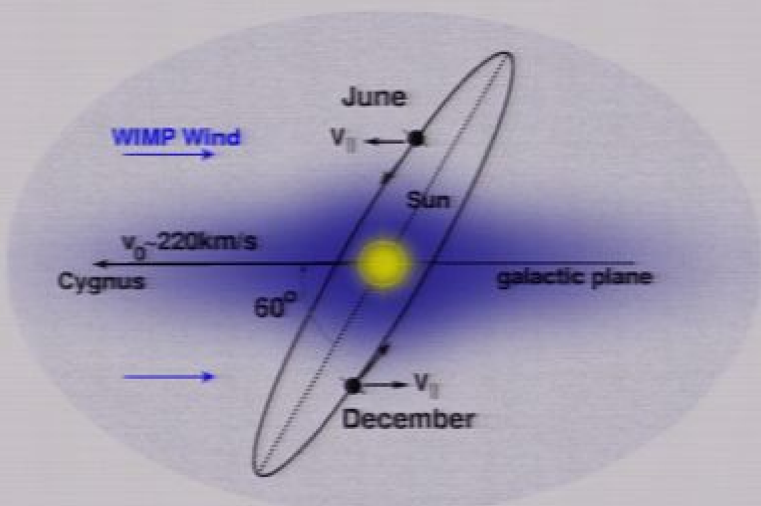
Null result ⇒ no Z coupling **OR** large splitting (and χ* unstable)

DAMA

One dark matter direct-detection experiment **has** already seen a signal:

arXiv:0804.2741, Bernabei et. al.



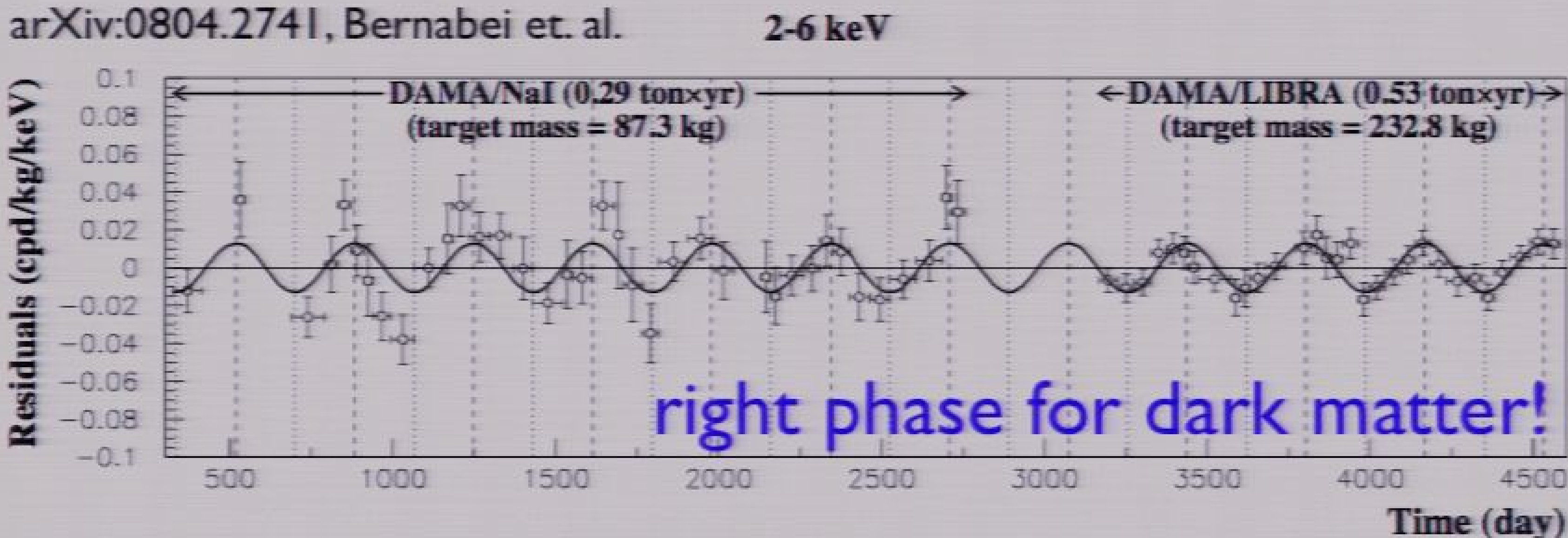


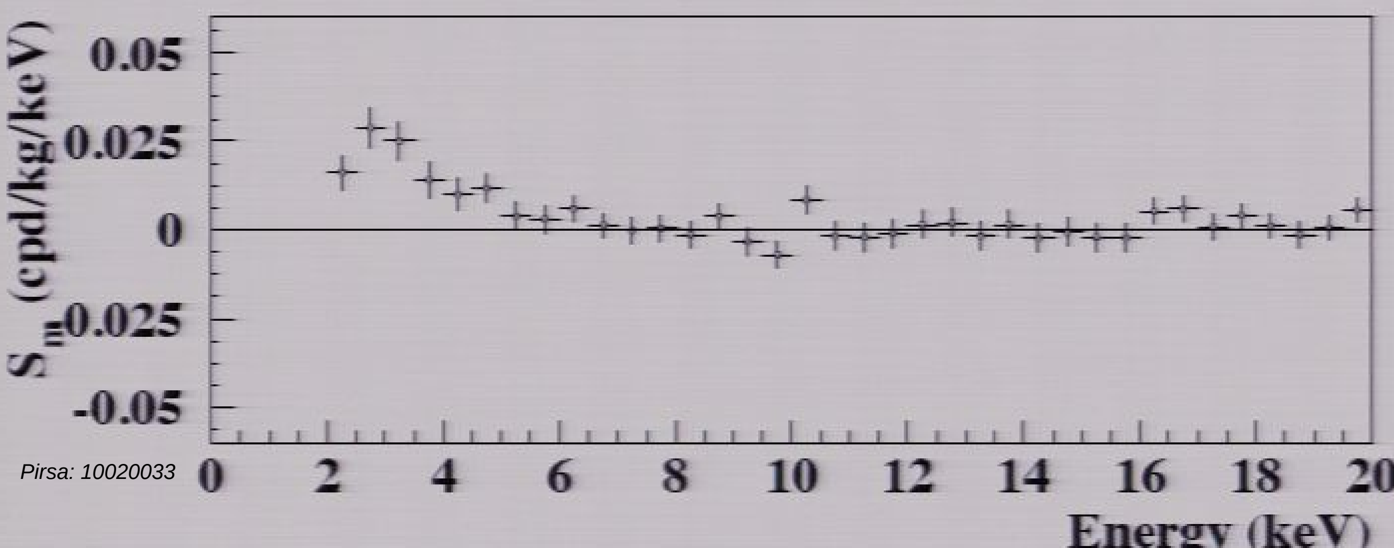
Big detector with no background rejection – just looked for annual modulation.

DAMA

One dark matter direct-detection experiment **has** already seen a signal:

arXiv:0804.2741, Bernabei et. al.

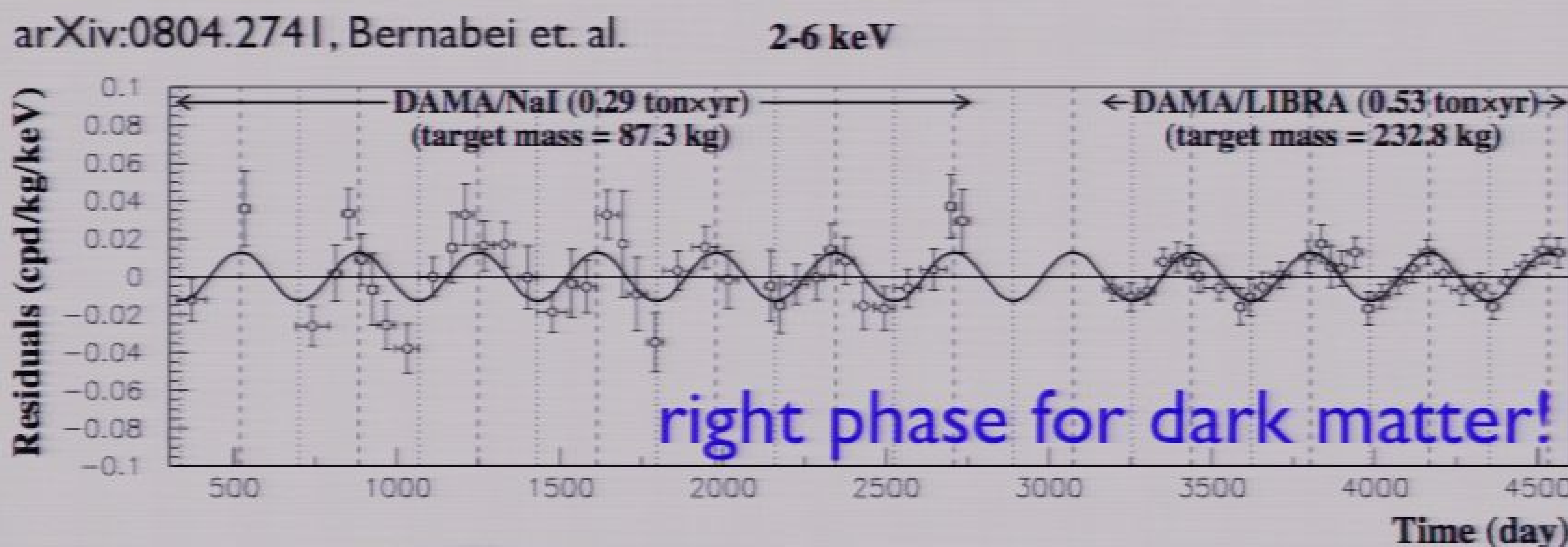


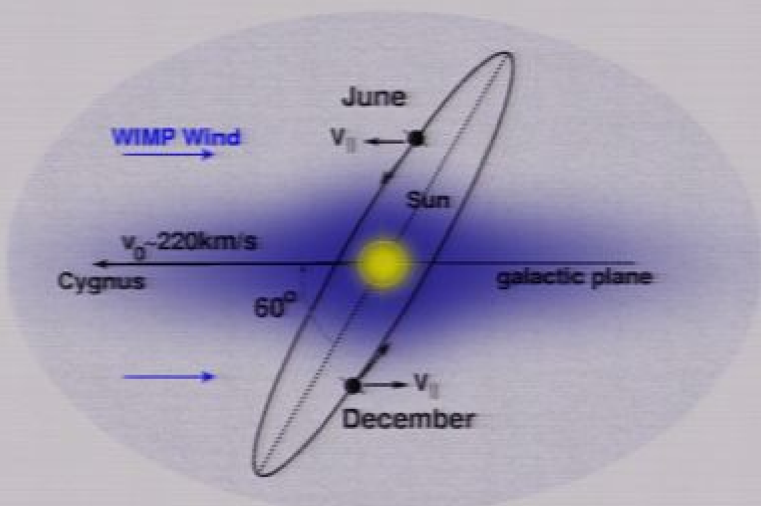


DAMA reported **modulation** rate comparable to total rate limits from CDMS, Xenon

DAMA

One dark matter direct-detection experiment **has** already seen a signal:



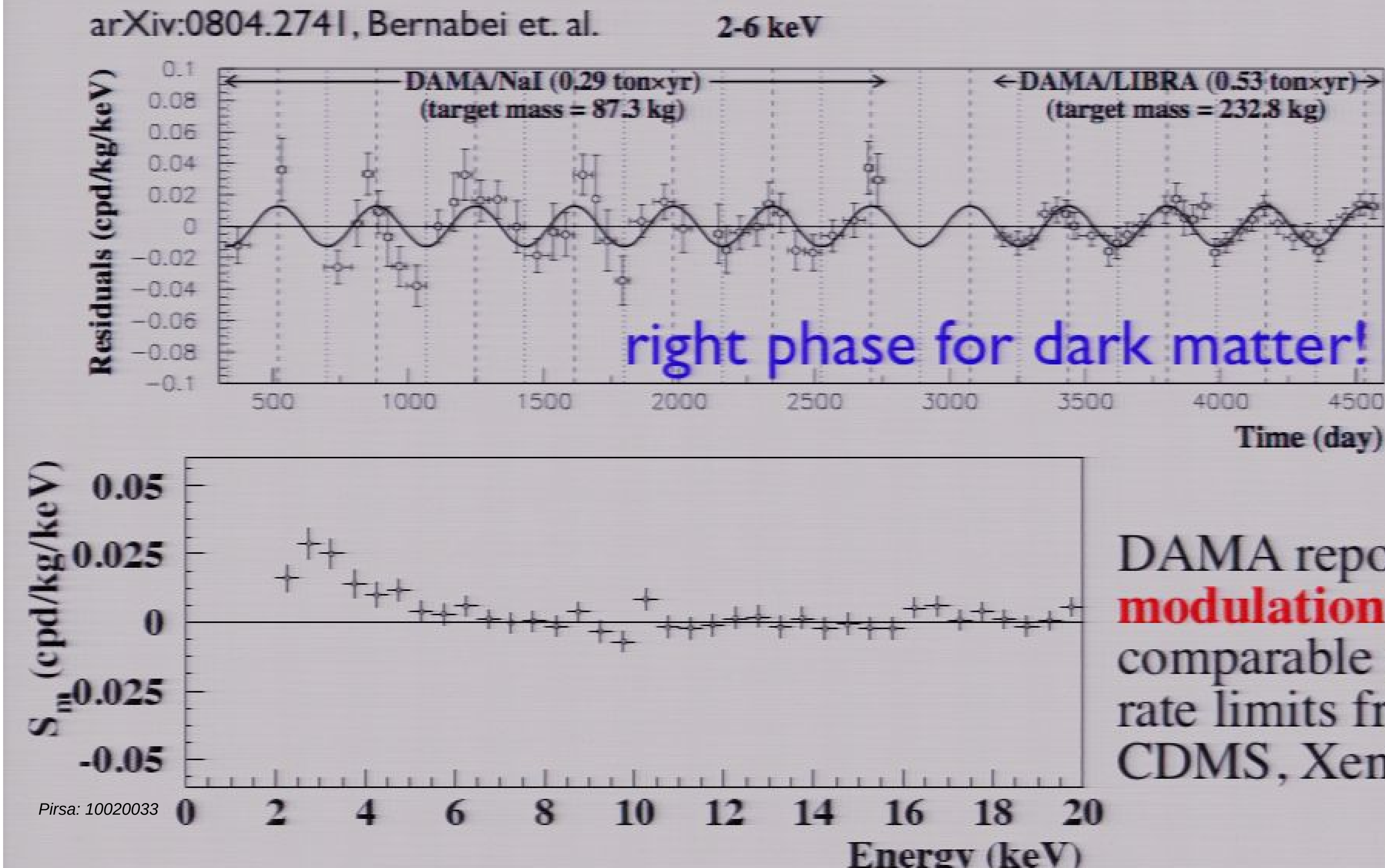


Big detector with no background rejection – just looked for annual modulation.

DAMA

One dark matter direct-detection experiment **has** already seen a signal:

arXiv:0804.2741, Bernabei et. al.



DAMA reported **modulation** rate comparable to total rate limits from CDMS, Xenon

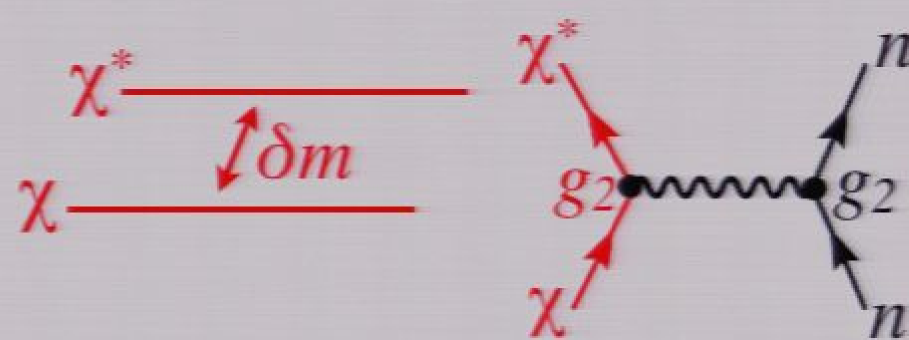
What kind of DM could be seen **first** at DAMA?

– Something scattering off e–

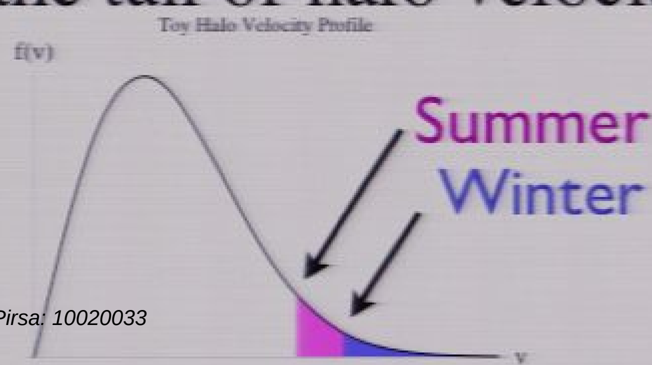
– Something with O(1) modulation fraction.

One possible origin: Z-mediated scattering, when δm ~ WIMP kinetic energy ~ 100 keV.

[Tucker-Smith & Weiner]



Key feature: kinetic-energy threshold is on the tail of halo velocity distribution:

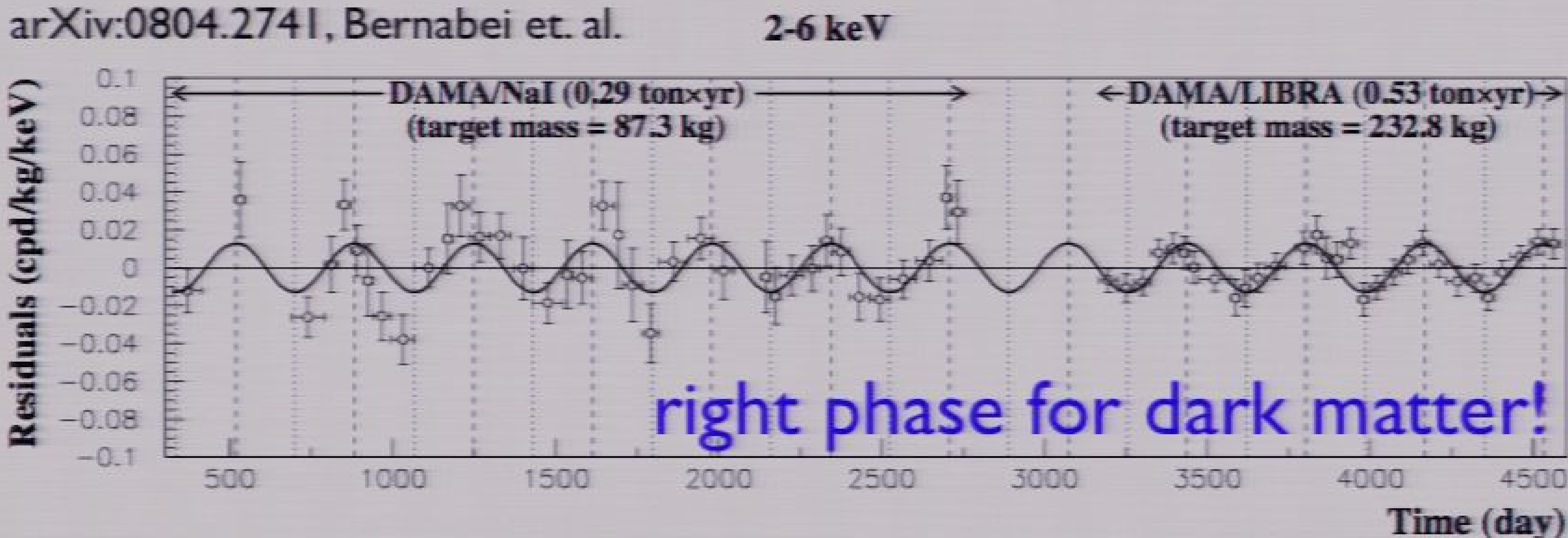


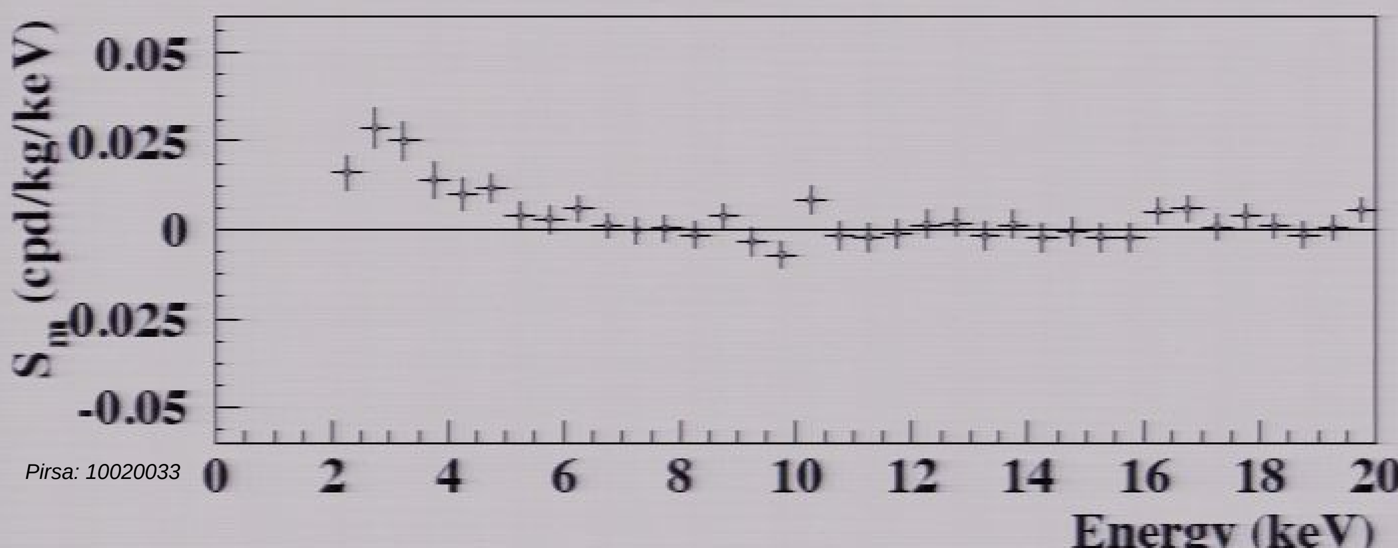
- O(1) annual modulation
- Near-threshold events have non-zero recoil energy
- Weak limits from low-A targets (CDMS)

DAMA

One dark matter direct-detection experiment **has** already seen a signal:

arXiv:0804.2741, Bernabei et. al.





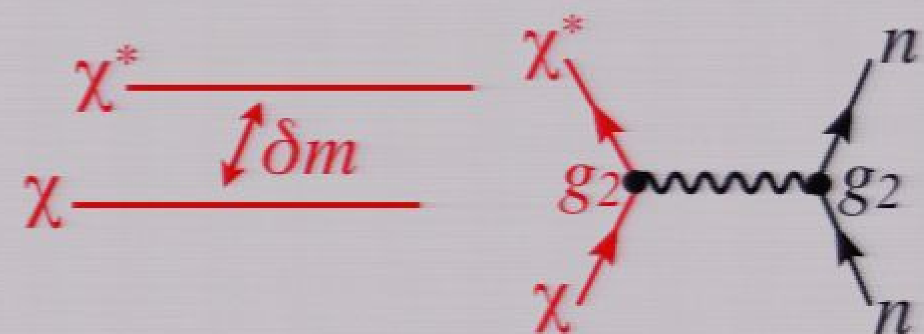
DAMA reported **modulation** rate comparable to total rate limits from CDMS, Xenon

What kind of DM could be seen **first** at DAMA?

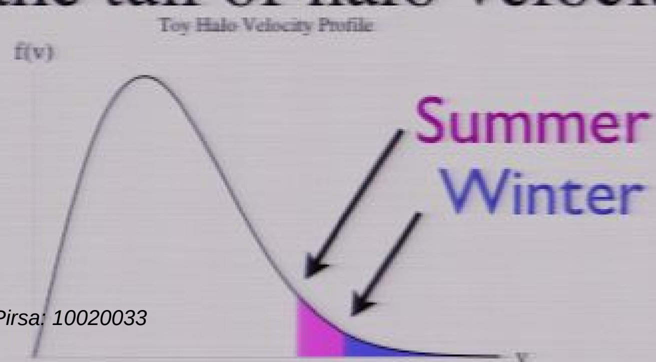
– Something scattering off e–
– Something with O(1) modulation fraction.

One possible origin: Z-mediated scattering, when δm ~ WIMP kinetic energy ~ 100 keV.

[Tucker-Smith & Weiner]



Key feature: kinetic-energy threshold is on the tail of halo velocity distribution:



- O(1) annual modulation
- Near-threshold events have non-zero recoil energy
- Weak limits from low-A targets (CDMS)

DAMA vs. Xenon 100

DAMA Modulation
~ 0.1 events/kg/day

XENON 100 expected background
(electron **and** nuclear)
~ 0.05 events/kg/day

⇘

100's of events in XENON 100
(50 kg x 100 days x acceptance)

XENON 100 can test hypotheses for DAMA *decisively*

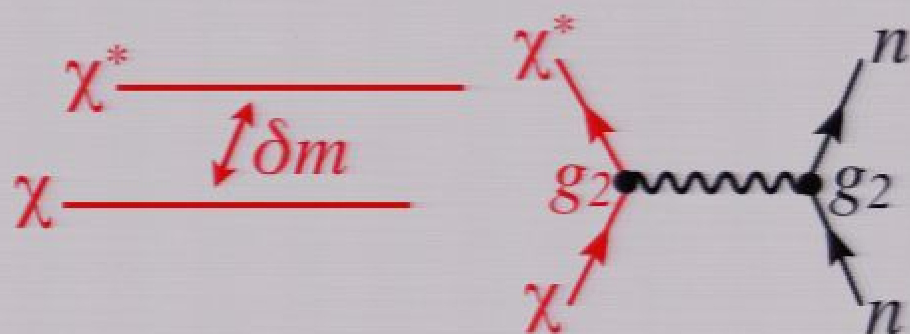
What kind of DM could be seen **first** at DAMA?

– Something scattering off e–

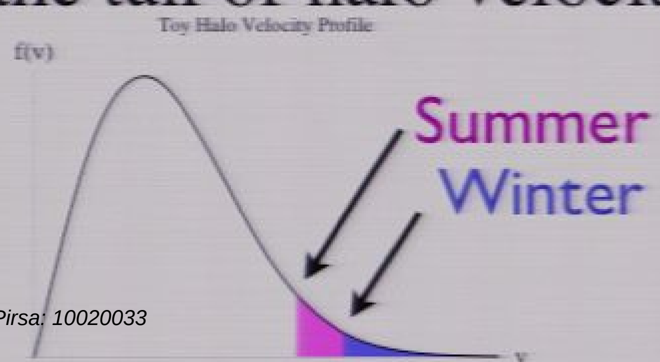
– Something with O(1) modulation fraction.

One possible origin: *Z*-mediated scattering, when δm ~ WIMP kinetic energy ~ 100 keV.

[Tucker-Smith & Weiner]



Key feature: kinetic-energy threshold is on the tail of halo velocity distribution:

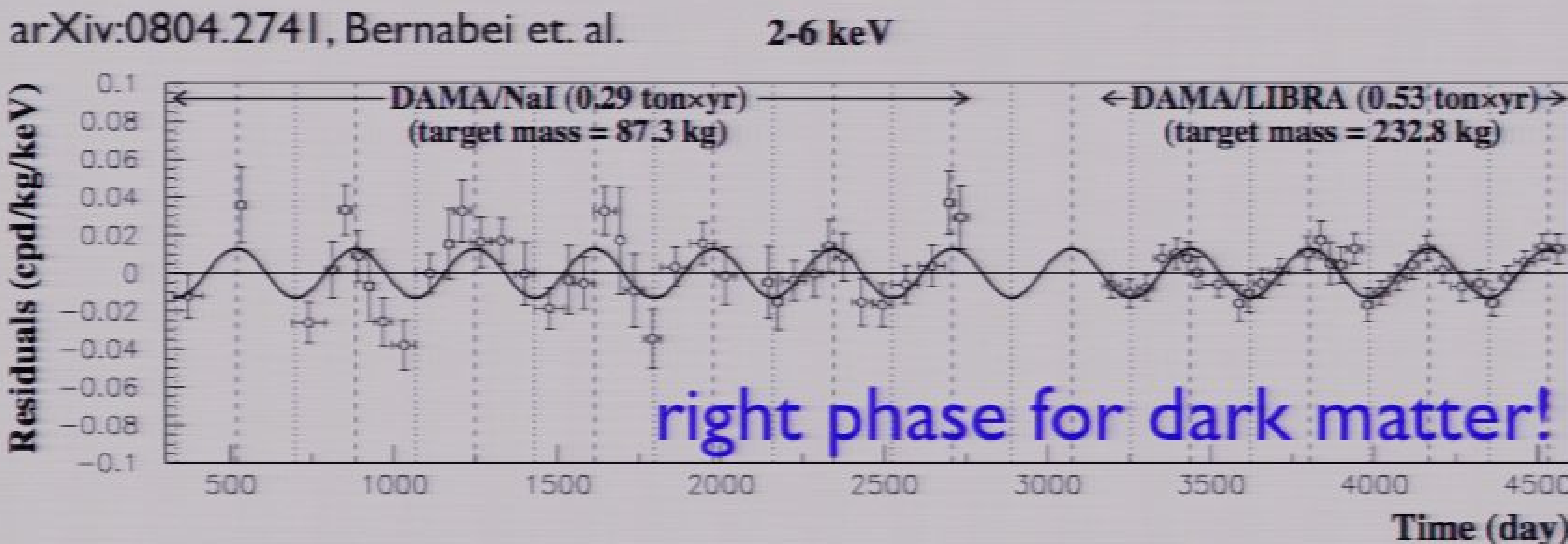


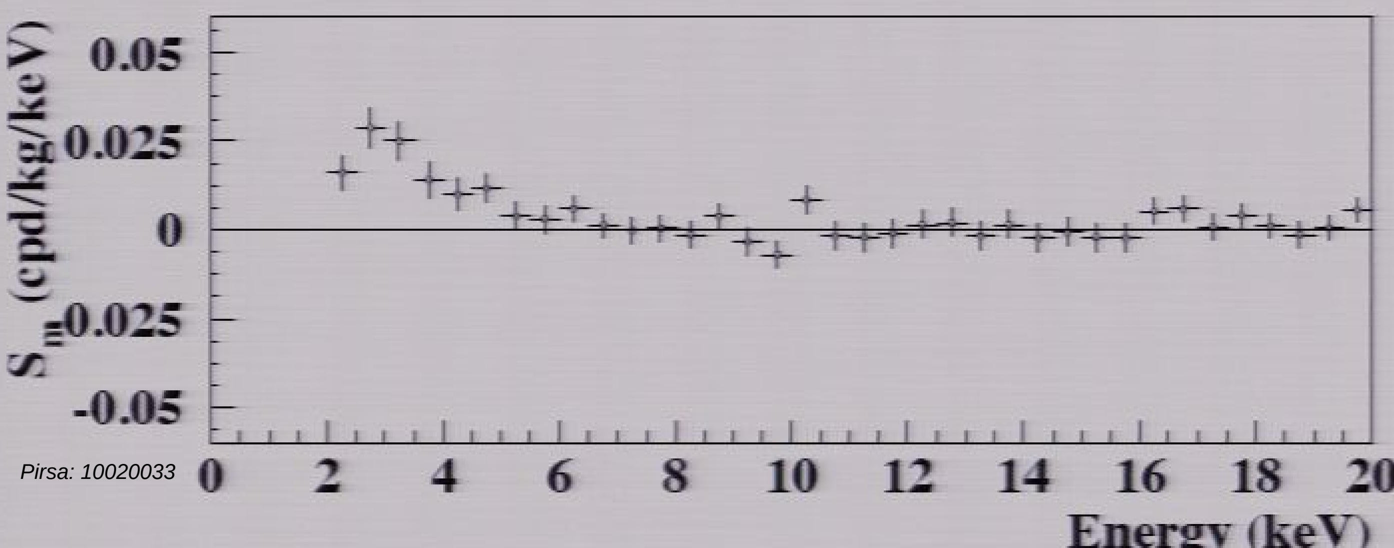
- O(1) annual modulation
- Near-threshold events have non-zero recoil energy
- Weak limits from low-*A* targets (CDMS)

DAMA

One dark matter direct-detection experiment **has** already seen a signal:

arXiv:0804.2741, Bernabei et. al.





DAMA reported **modulation** rate comparable to total rate limits from CDMS, Xenon

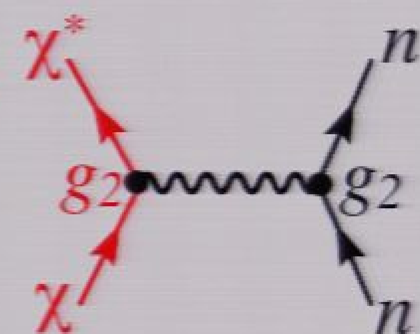
What kind of DM could be seen **first** at DAMA?

– Something scattering off e–

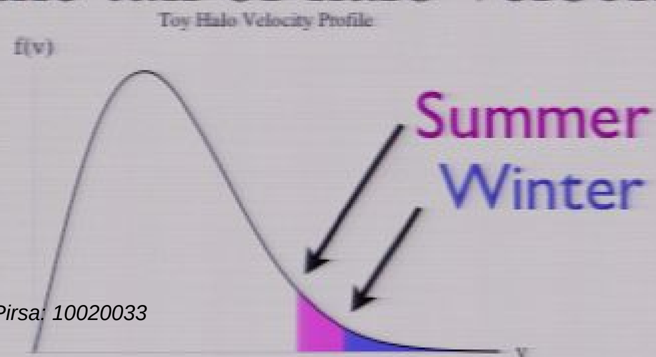
– Something with O(1) modulation fraction.

One possible origin: *Z*-mediated scattering, when δm ~ WIMP kinetic energy ~ 100 keV.

[Tucker-Smith & Weiner]



Key feature: kinetic-energy threshold is on the tail of halo velocity distribution:



- O(1) annual modulation
- Near-threshold events have non-zero recoil energy
- Weak limits from low-*A* targets (CDMS)

DAMA vs. Xenon 100

XENON 100 expected background

DAMA Modulation
~ 0.1 events/kg/day

(electron **and** nuclear)
~ 0.05 events/kg/day

⇘

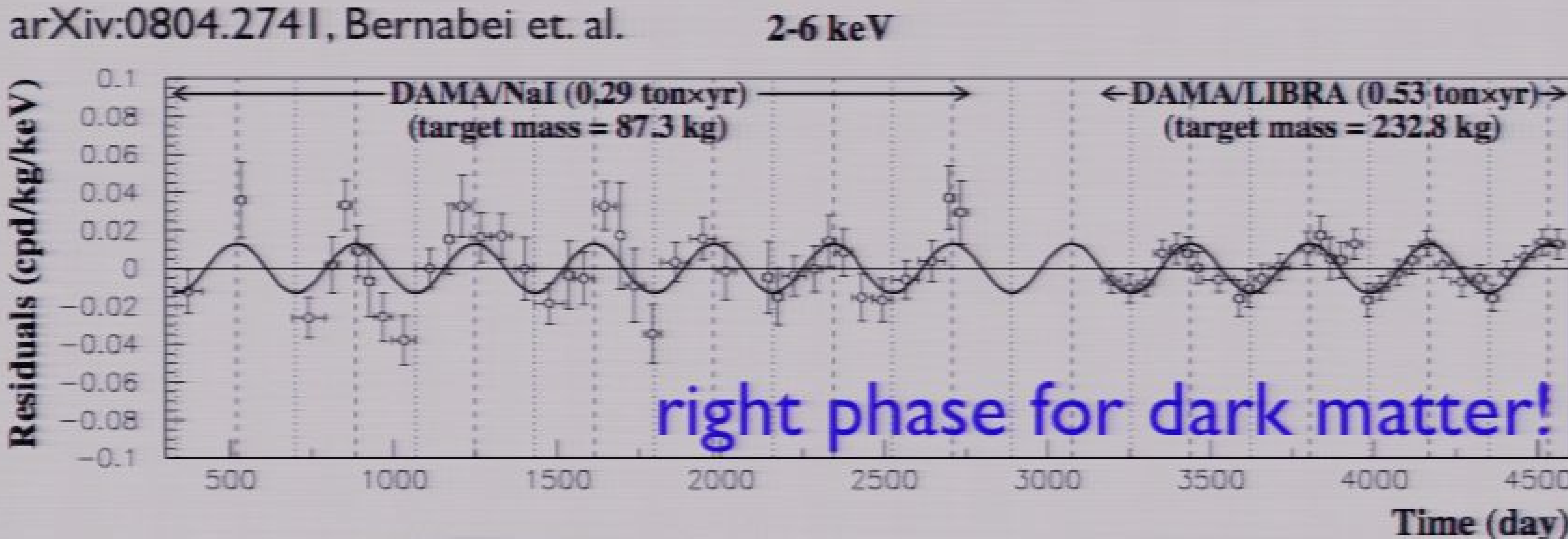
100's of events in XENON 100
(50 kg x 100 days x acceptance)

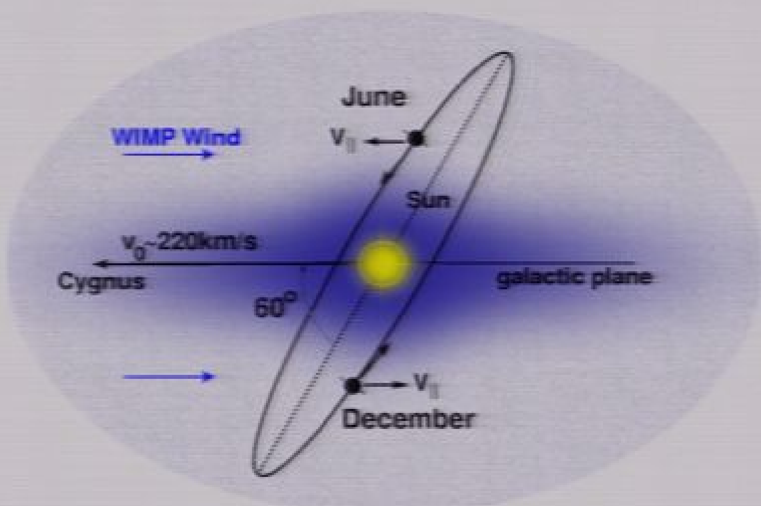
XENON 100 can test hypotheses for DAMA *decisively*

DAMA

One dark matter direct-detection experiment **has** already seen a signal:

arXiv:0804.2741, Bernabei et. al.





Big detector with no background rejection – just looked for annual modulation.

Z-Mediated Scattering, reconsidered

Massive spin-1 fields mediate typically off-diagonal interactions:

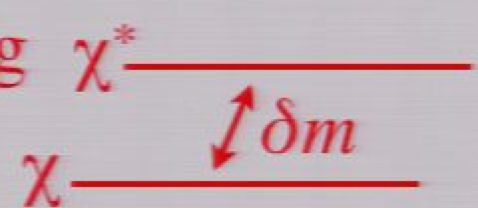
e.g. Complex scalar field $\varphi = \phi_1 + i\phi_2$

Gauge interaction $D_\mu \varphi^* D^\mu \varphi \to q A^\mu (\phi_1 \partial_\mu \phi_2 - \phi_2 \partial_\mu \phi_1)$

Most general mass matrix splits ϕ_1 and ϕ_2

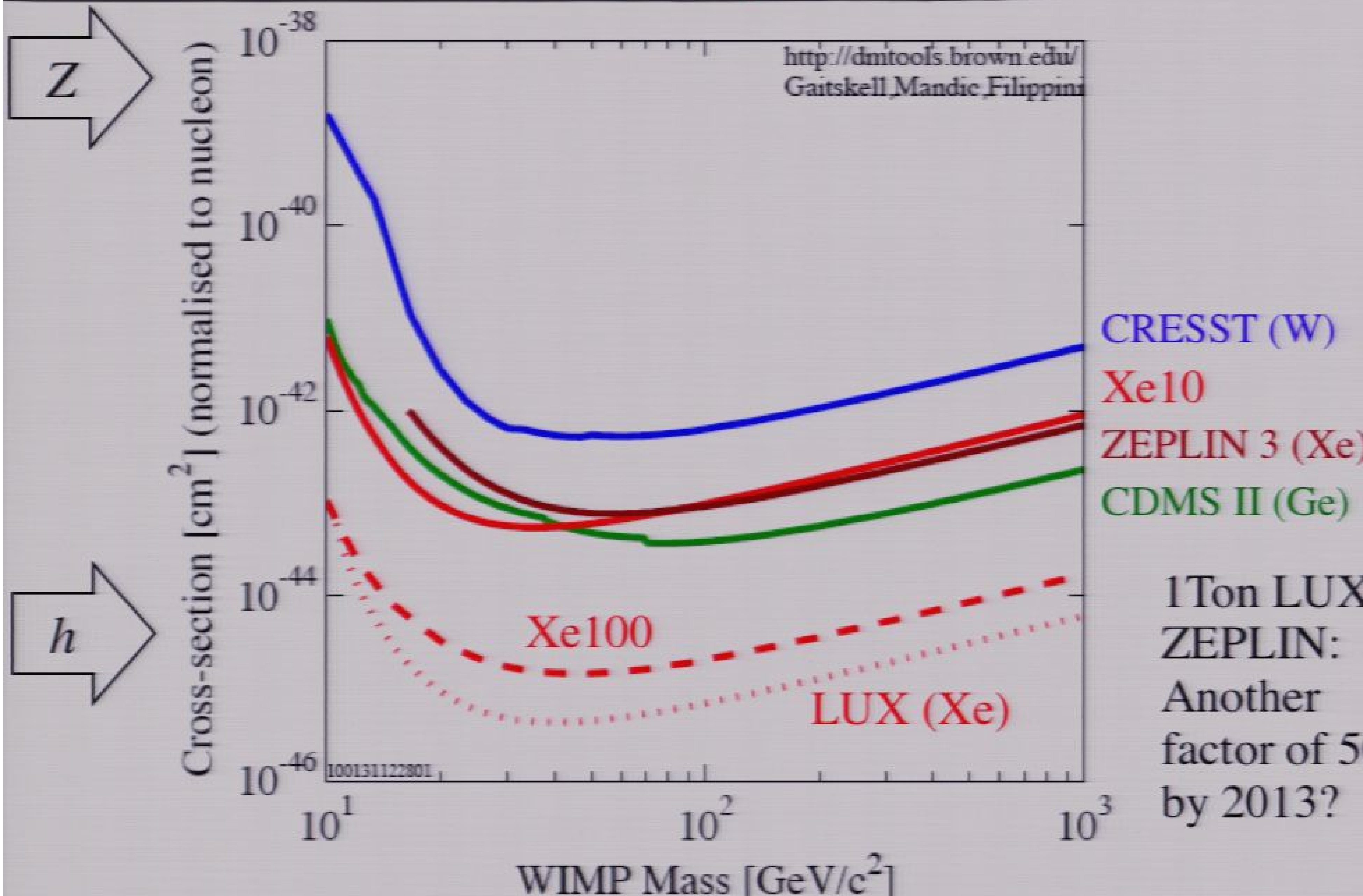
Standard Model: *W* couplings *are* mass off-diagonal; splittings in *Z* exchange forbidden by $U(1)_{EM}$.

$\Rightarrow$ Inelastic dark matter scattering



Null result $\Rightarrow$ no *Z* coupling **OR** large splitting (and χ^* unstable)

Current and Future Sensitivity



1Ton LUX/ ZEPLIN: Another factor of 50 by 2013?

Current sensitivity ~10^{-42} cm^2 — no *Z* interaction?

Z-Mediated Scattering, reconsidered

Massive spin-1 fields mediate typically off-diagonal interactions:

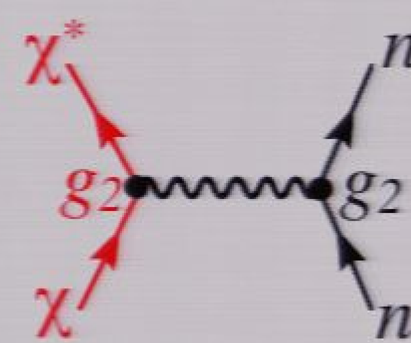
e.g. Complex scalar field $\varphi = \phi_1 + i\phi_2$

Gauge interaction $D_\mu \varphi^* D^\mu \varphi \to q A^\mu (\phi_1 \partial_\mu \phi_2 - \phi_2 \partial_\mu \phi_1)$

Most general mass matrix splits ϕ_1 and ϕ_2

Standard Model: *W* couplings *are* mass off-diagonal; splittings in *Z* exchange forbidden by $U(1)_{EM}$.

⇒Inelastic dark matter scattering

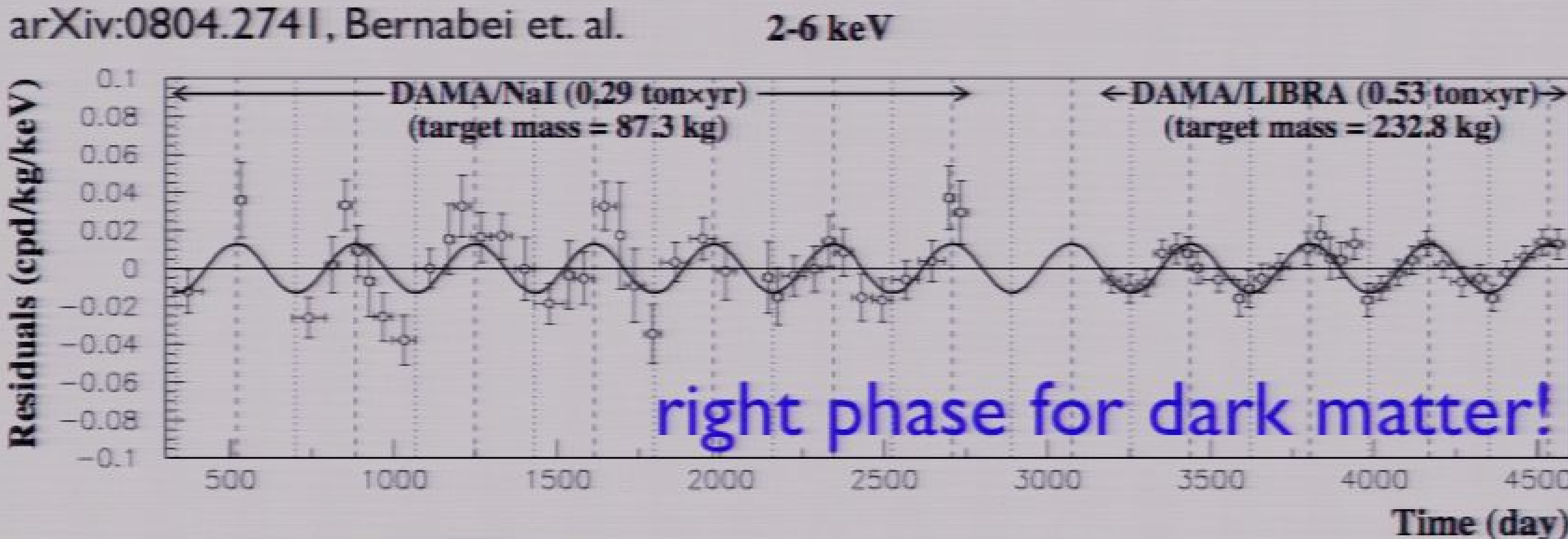


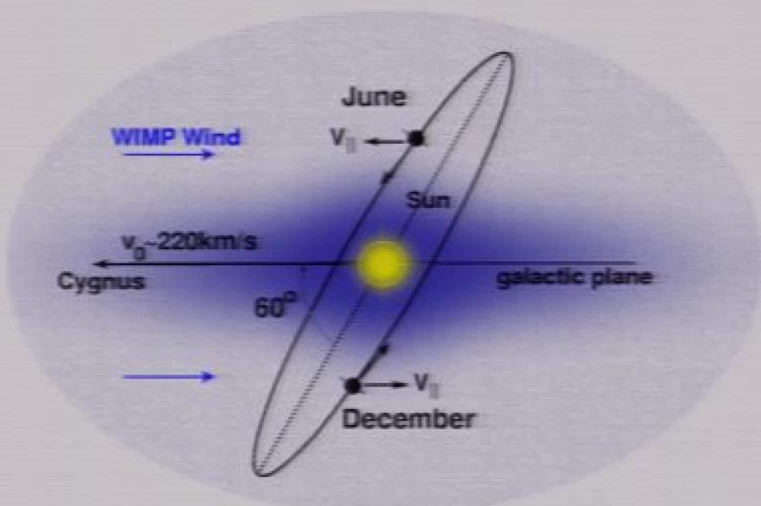
Null result ⇒ no *Z* coupling **OR** large splitting (and χ^* unstable)

DAMA

One dark matter direct-detection experiment **has** already seen a signal:

arXiv:0804.2741, Bernabei et. al.

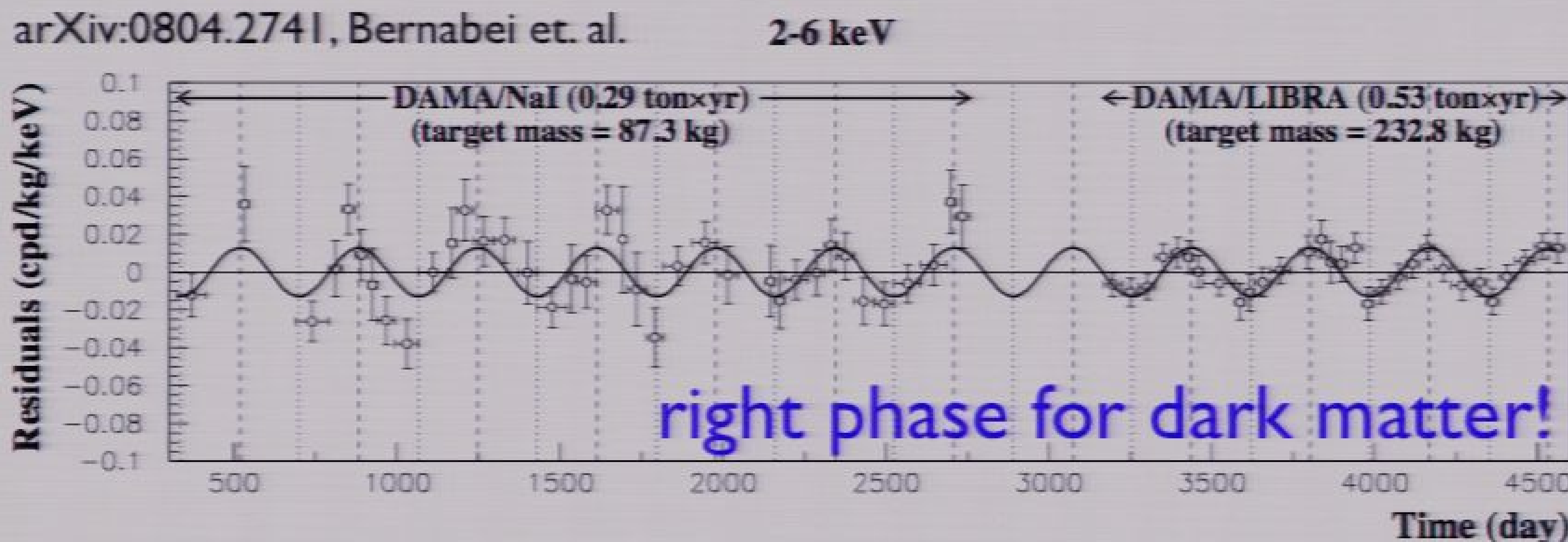


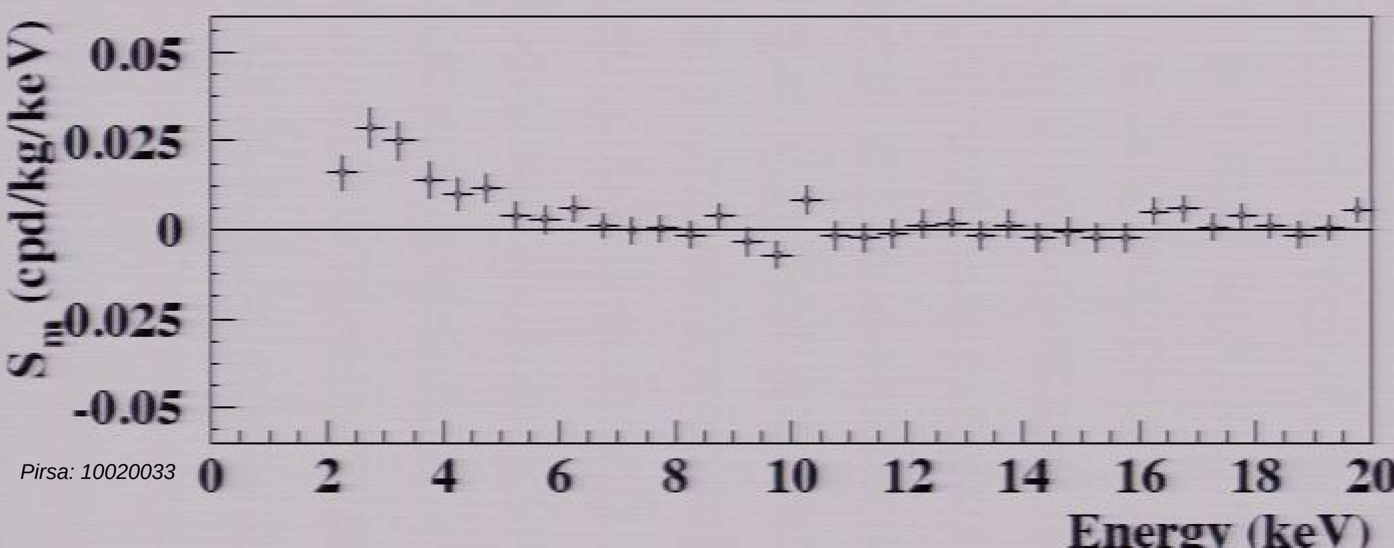


Big detector with no background rejection – just looked for annual modulation.

DAMA

One dark matter direct-detection experiment **has** already seen a signal:





DAMA reported **modulation** rate comparable to total rate limits from CDMS, Xenon

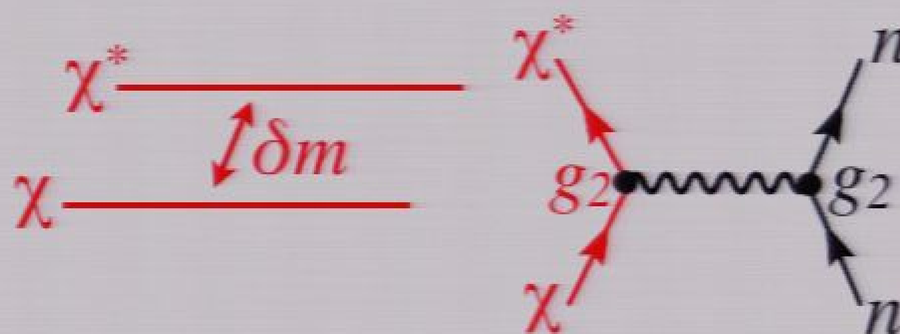
What kind of DM could be seen **first** at DAMA?

– Something scattering off e–

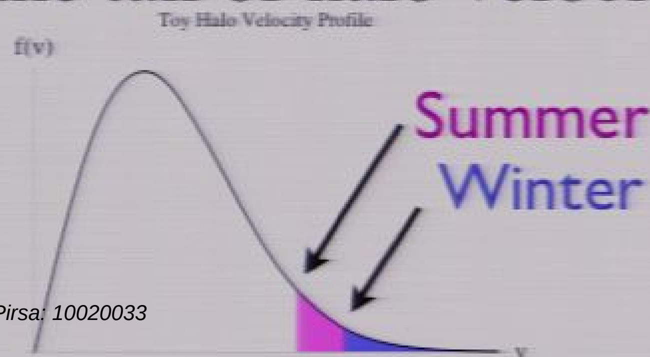
– Something with O(1) modulation fraction.

One possible origin: *Z*-mediated scattering, when δm ~ WIMP kinetic energy ~ 100 keV.

[Tucker-Smith & Weiner]



Key feature: kinetic-energy threshold is on the tail of halo velocity distribution:

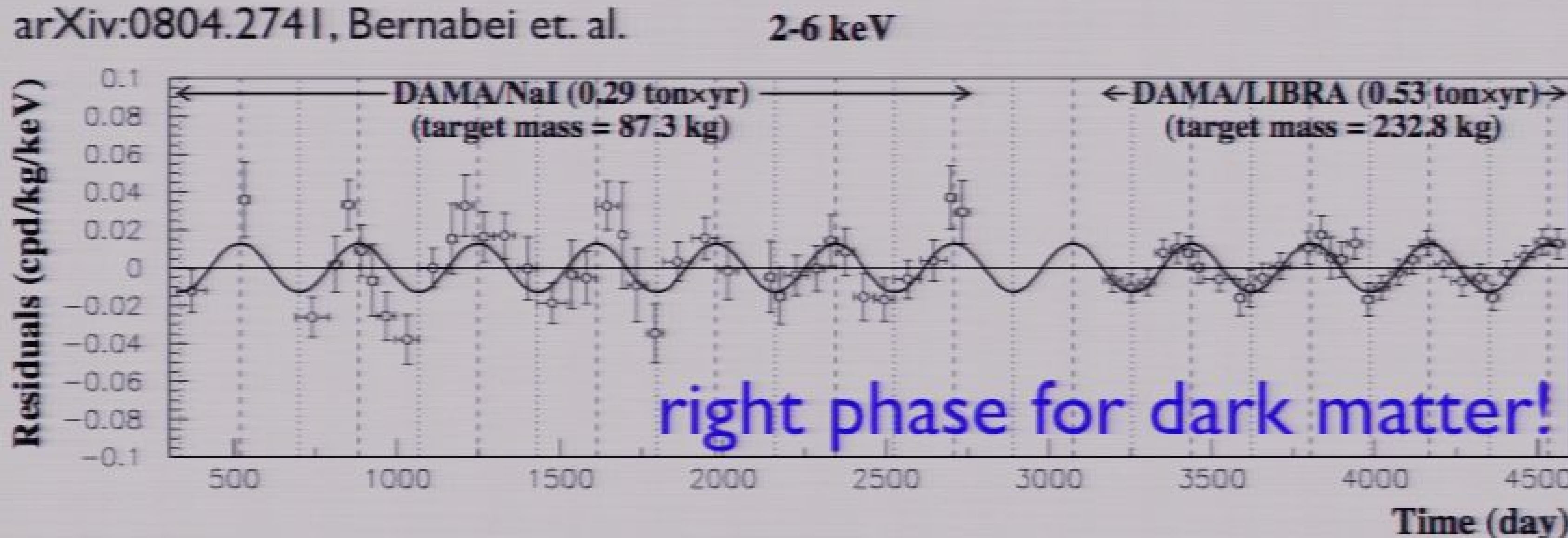


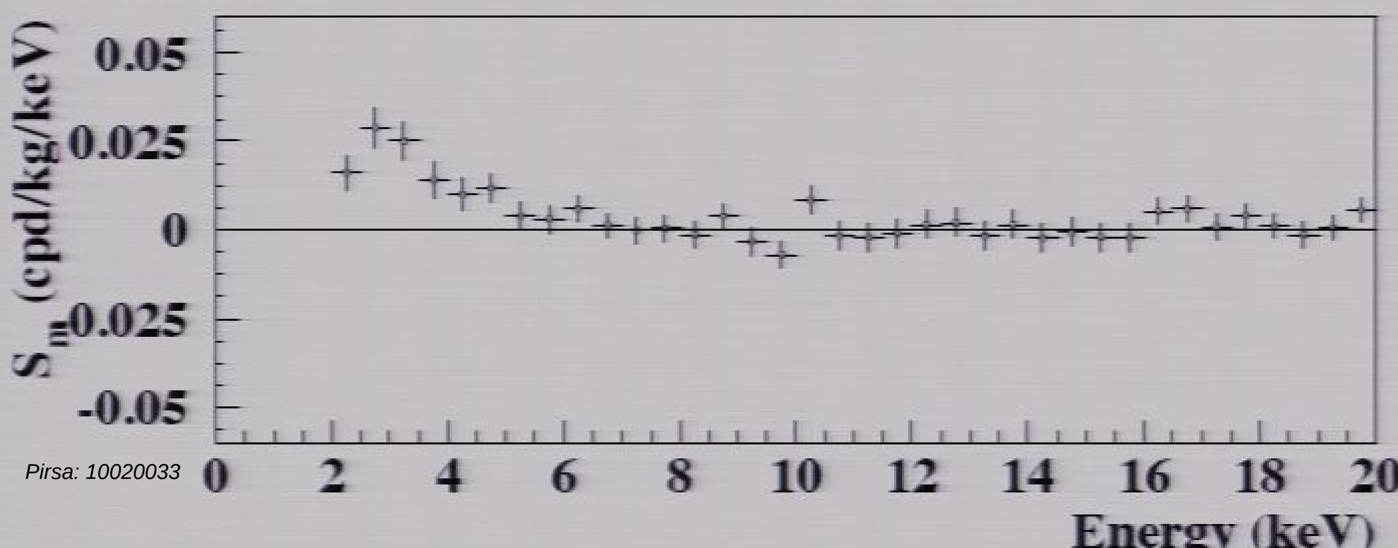
- O(1) annual modulation
- Near-threshold events have non-zero recoil energy
- Weak limits from low-*A* targets (CDMS)

DAMA

One dark matter direct-detection experiment **has** already seen a signal:

arXiv:0804.2741, Bernabei et. al.





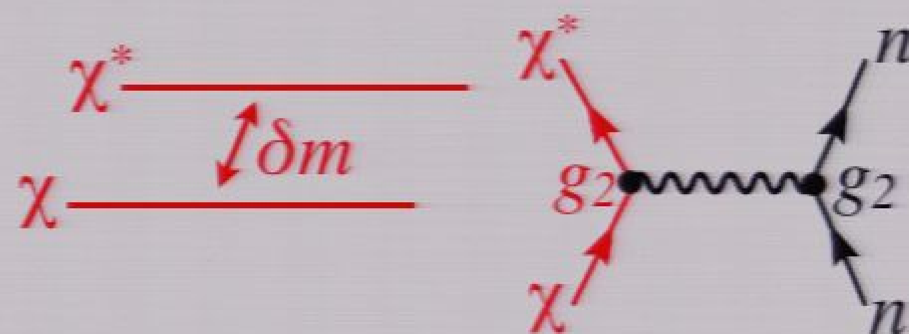
DAMA reported **modulation** rate comparable to total rate limits from CDMS, Xenon

What kind of DM could be seen **first** at DAMA?

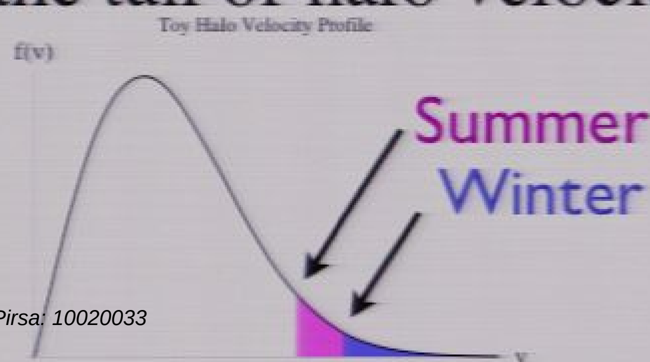
– Something scattering off e–
– Something with O(1) modulation fraction.

One possible origin: Z-mediated scattering, when δm ~ WIMP kinetic energy ~ 100 keV.

[Tucker-Smith & Weiner]



Key feature: kinetic-energy threshold is on the tail of halo velocity distribution:



- O(1) annual modulation
- Near-threshold events have non-zero recoil energy
- Weak limits from low-A targets (CDMS)

DAMA vs. Xenon 100

DAMA Modulation
~ 0.1 events/kg/day

XENON 100 expected background
(electron **and** nuclear)
~ 0.05 events/kg/day

⇘

100's of events in XENON 100
(50 kg x 100 days x acceptance)

XENON 100 can test hypotheses for DAMA *decisively*

DAMA vs. Xenon 100

DAMA Modulation
~ 0.1 events/kg/day

XENON 100 expected background
(electron **and** nuclear)
~ 0.05 events/kg/day

⇘

100's of events in XENON 100
(50 kg x 100 days x acceptance)

XENON 100 can test hypotheses for DAMA *decisively*

Coming Results in Direct Detection

- Is DAMA observing WIMP-matter interaction?
- Confirm that dark matter is a particle!
- Probe two basic standard model couplings:
  - higgs coupling
  - Z coupling (with mass splittings)
  - Start learning: Is Dark Matter a "part of" the Standard Model (same gauge interactions), or not?

Dark Matter Annihilation (Indirect Detection)

General approach: search for products of dark matter annihilation or decay (on $\gg$ cosmological timescales) within the galaxy:

- electrons and positrons
- anti-protons
- gamma-rays

Whereas direct scattering searches can say how much Dark Matter interacts with ordinary matter, annihilation searches may tell us what else it couples to.

TeV dark matter annihilation: as much energy as an LHC collision, potentially very different interactions.

Indirect Detection

General approach: search for products of dark matter annihilation or decay (on ≫ cosmological timescales) within the galaxy:

- electrons and positrons
- anti-protons
- gamma-rays

Challenge: astrophysical backgrounds are large, difficult to model

- e^+/e^- signals and astro. backgrounds are diffuse.
- γ–rays point back to source, but dark-matter search regions are also background-rich (e.g. galactic center)

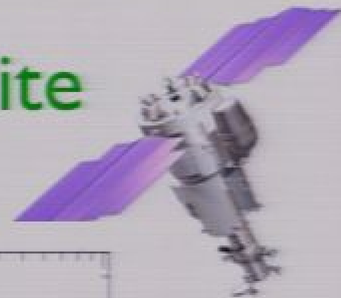
Anomalies don't have to inspire confidence, just new ideas…

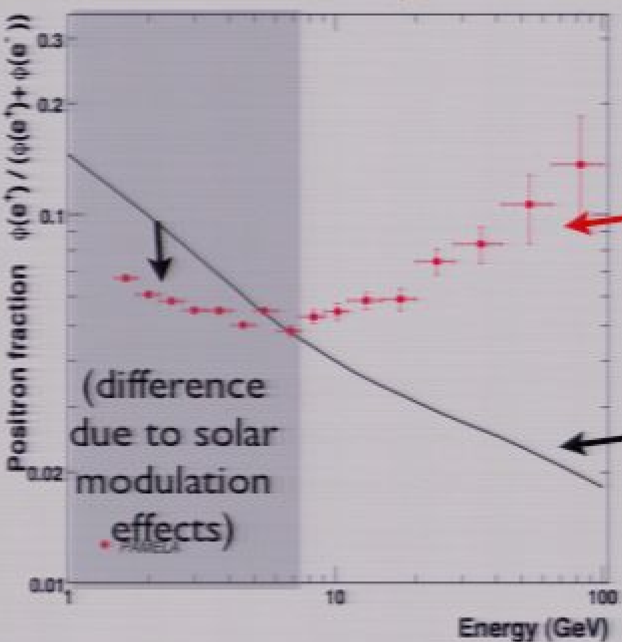
From this perspective, indirect detection has been very exciting in the last ~1.5 years!

A New Source of e^+e^-

PAMELA satellite

Nature, 2009
(~1 citation/day)

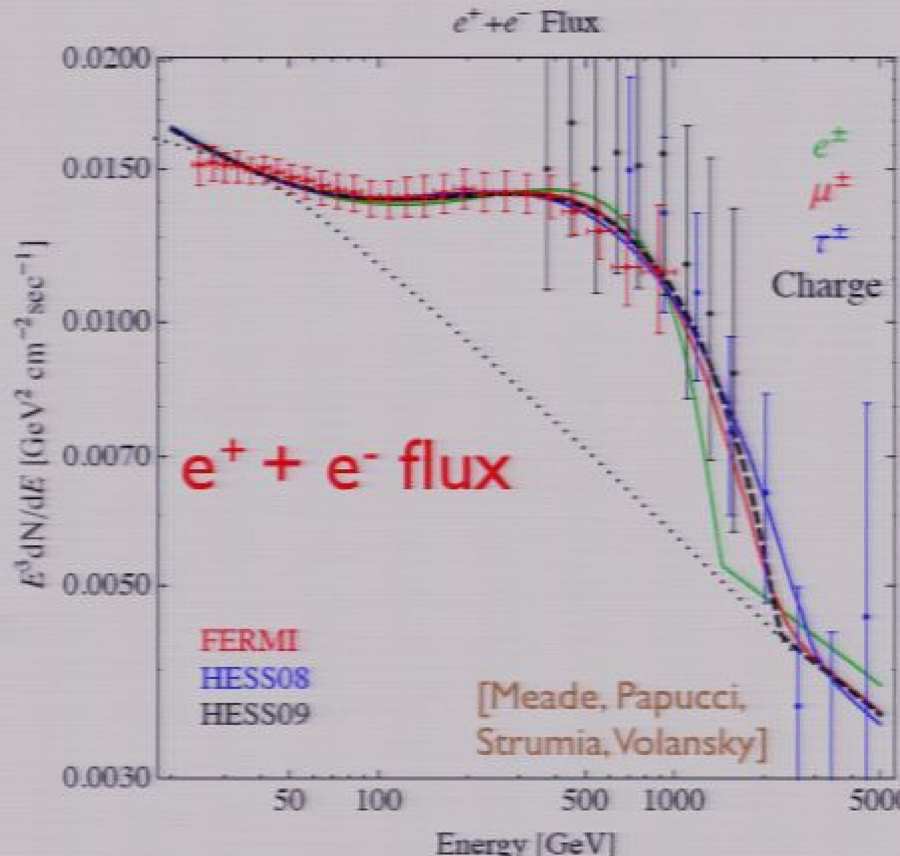




New e+ source

theory expectation

Fermi satellite, HESS



No B field – can't distinguish e^+ from e^-

Indirect Detection

General approach: search for products of dark matter annihilation or decay (on ≫ cosmological timescales) within the galaxy:

- electrons and positrons
- anti-protons
- gamma-rays

Challenge: astrophysical backgrounds are large, difficult to model

- e^+/e^- signals and astro. backgrounds are diffuse.
- γ–rays point back to source, but dark-matter search regions are also background-rich (e.g. galactic center)

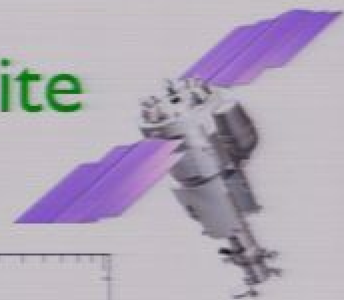
Anomalies don't have to inspire confidence, just new ideas…

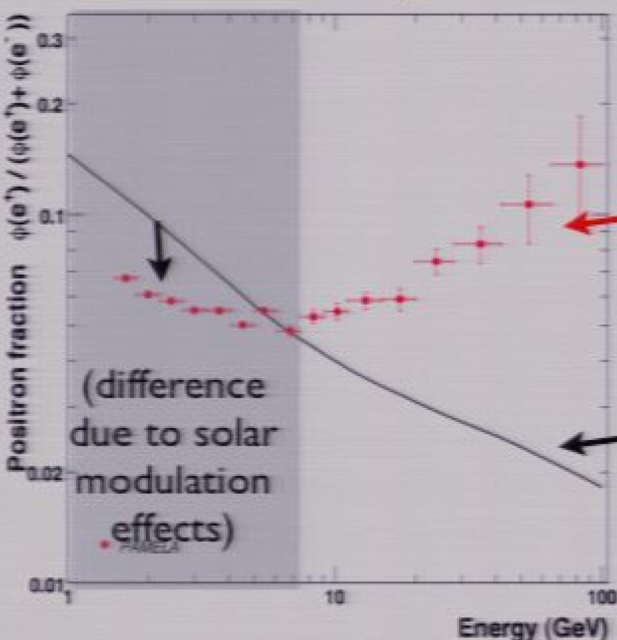
From this perspective, indirect detection has been very exciting in the last ~1.5 years!

A New Source of e^+e^-

PAMELA satellite

Nature, 2009
(~1 citation/day)

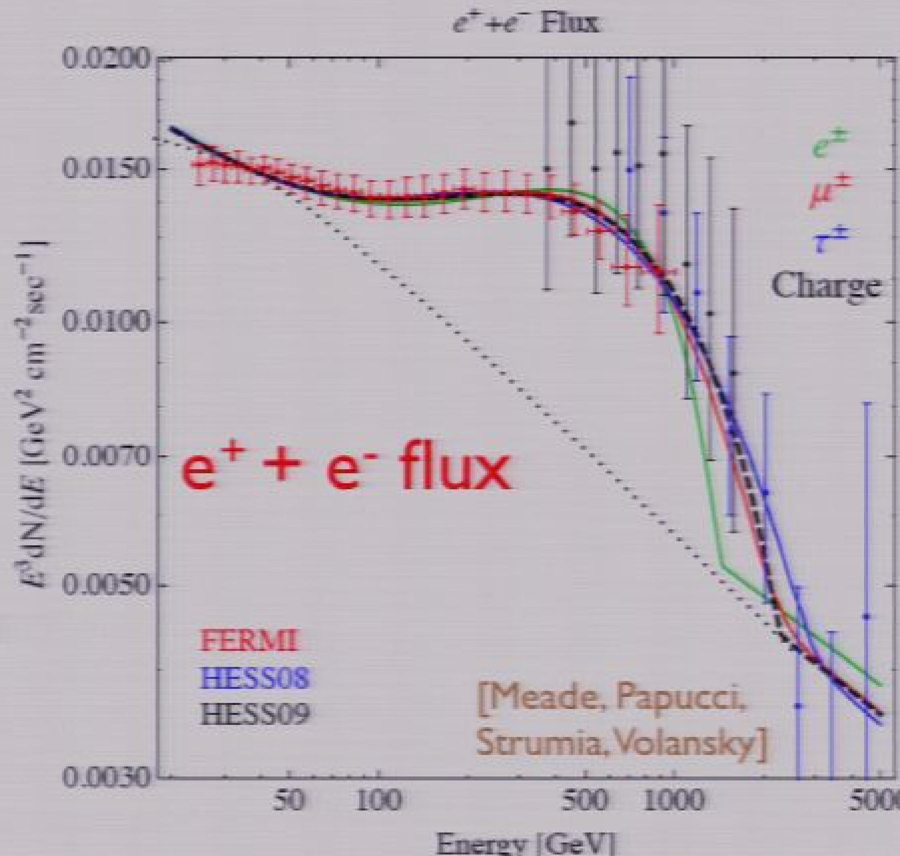




New e+ source

theory expectation

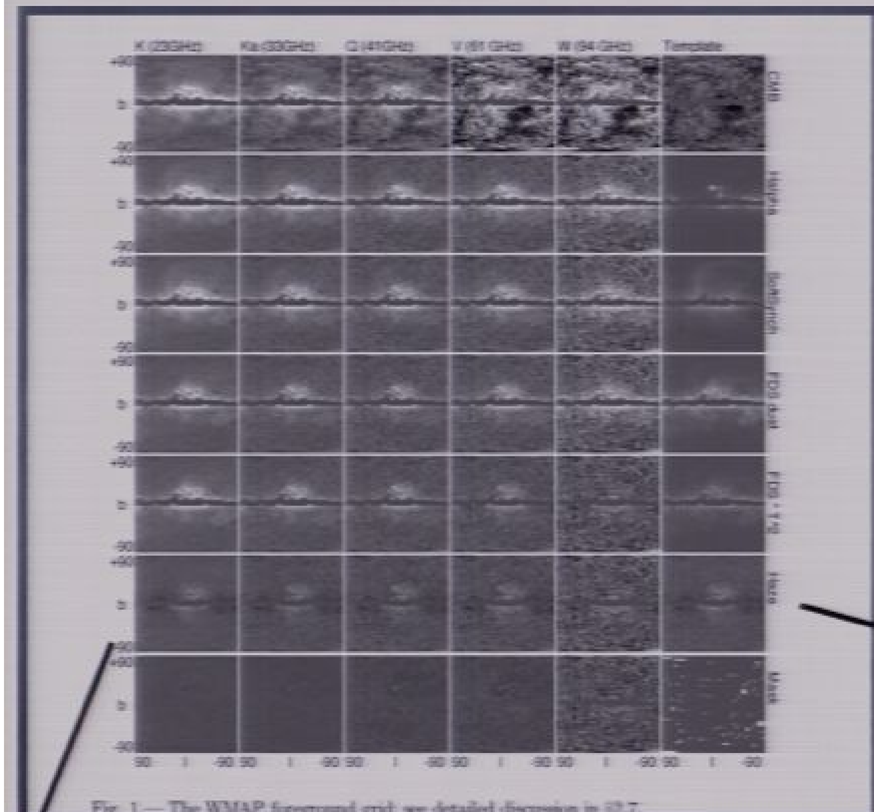
Fermi satellite, HESS



No B field – can't distinguish e^+ from e^-

Near the Galactic Center?

Microwave haze in WMAP data?



Suggestive of synchrotron from an e^+ excess in inner 20° of galaxy?

[Finkbeiner; Dobler, Finkbeiner]

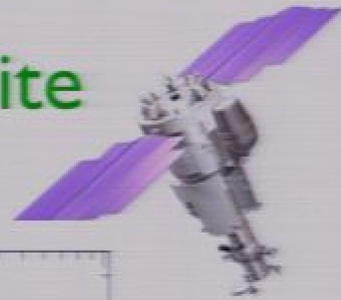
Similar morphology in γ-rays (inverse Compton scattering of starlight off same e^+ population?)

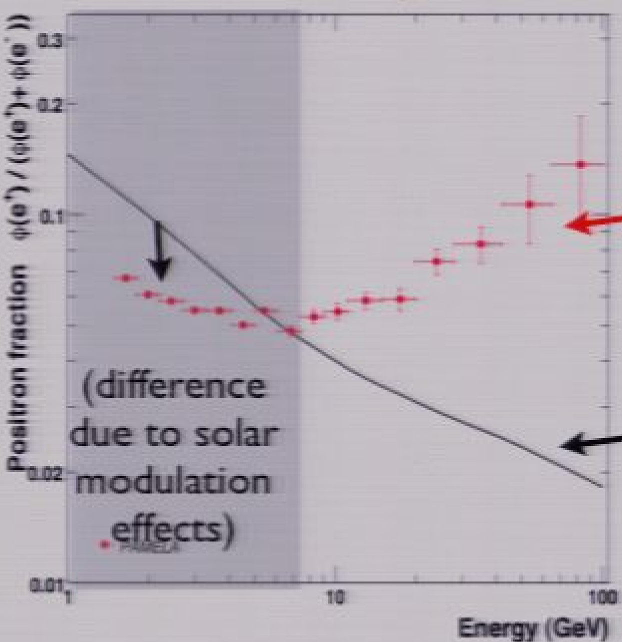
[Dobler, Finkbeiner, Slatyer, Weiner]

A New Source of e^+e^-

PAMELA satellite

Nature, 2009
(~1 citation/day)

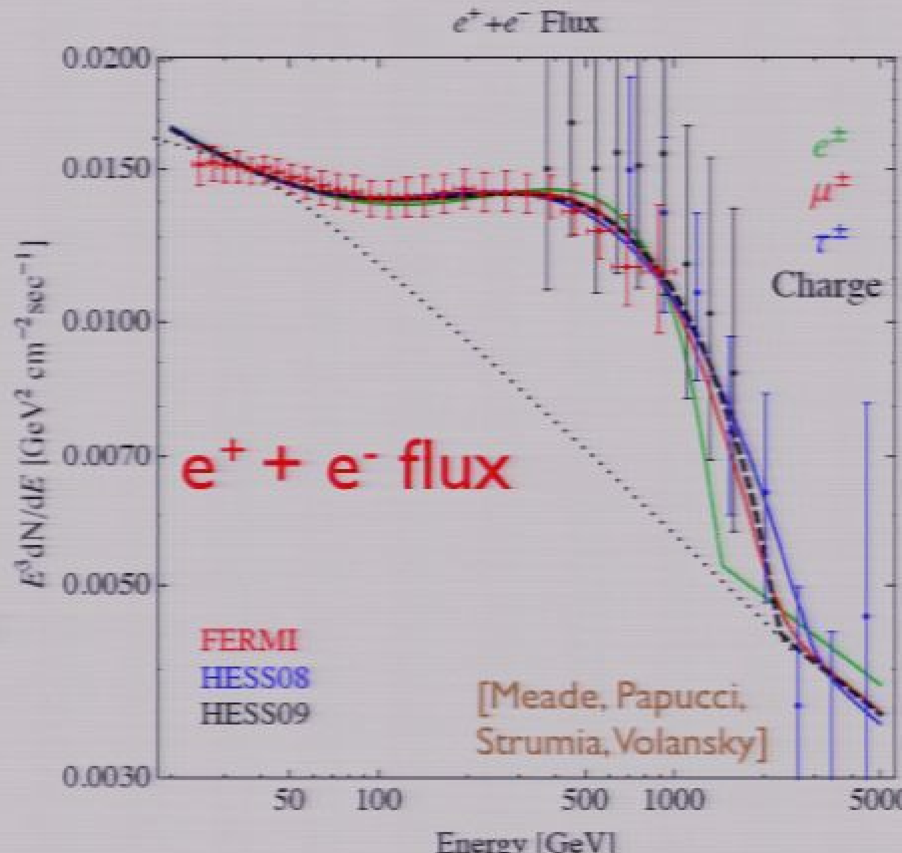




New e+ source

theory expectation

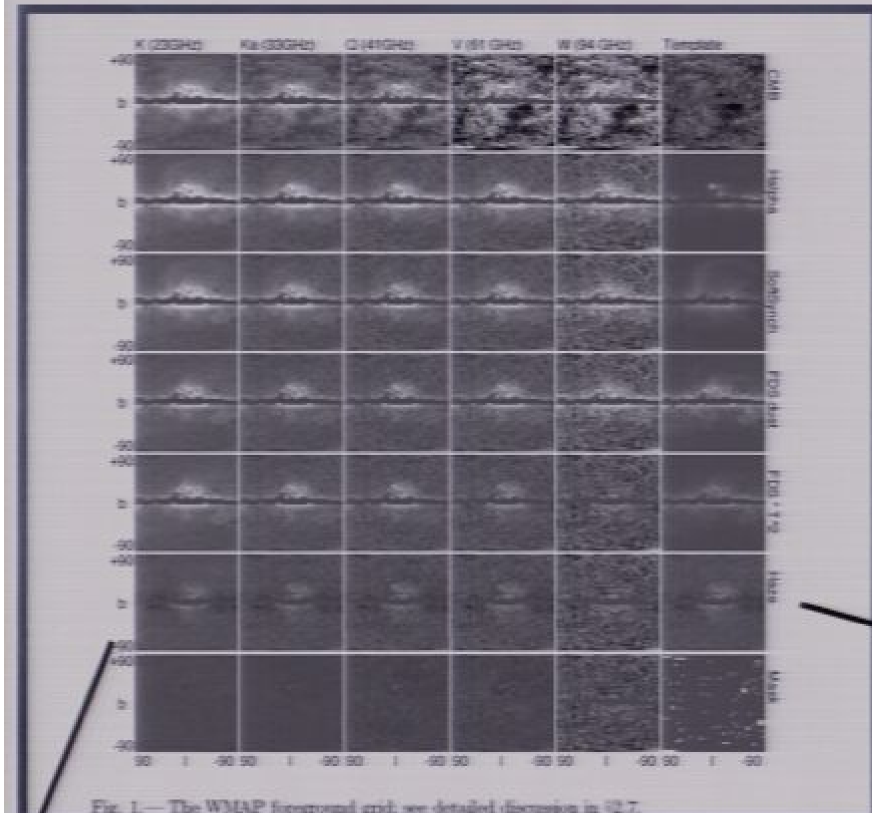
Fermi satellite, HESS



No B field – can't distinguish e^+ from e^-

Near the Galactic Center?

Microwave haze in WMAP data?



Suggestive of synchrotron from an e^+ excess in inner 20° of galaxy?
[Finkbeiner; Dobler, Finkbeiner]

Similar morphology in γ-rays (inverse Compton scattering of starlight off same e^+ population?)
[Dobler, Finkbeiner, Slatyer, Weiner]

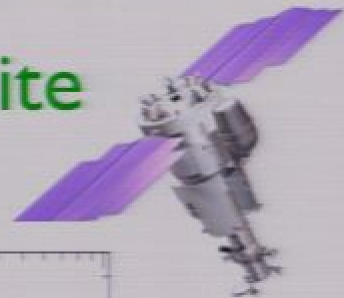
Future Searches

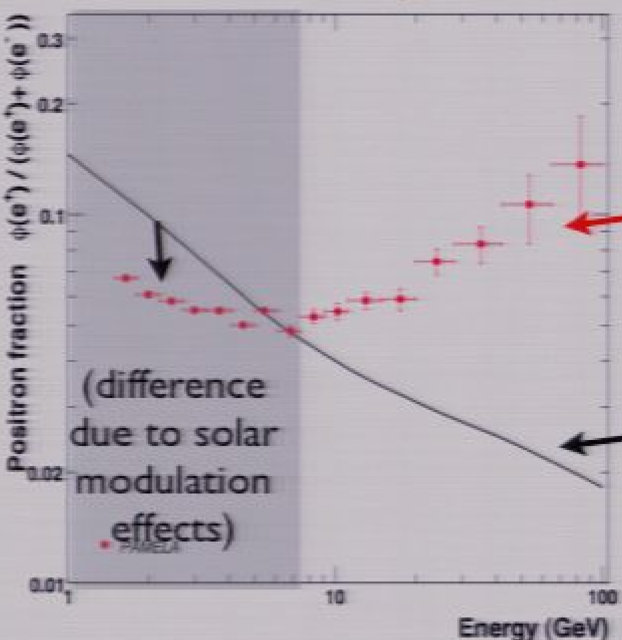
- AMS-II : much improved e+ and e– data
  - Scheduled to launch July 2010
  - Similar strategy to PAMELA, two advantages:
    - 50x larger area ⇒ higher statistics
    - distinguish charges up to higher energy (400-1000 GeV)
- FERMI γ-ray analyses : look elsewhere in Milky Way halo
  - Model-based searches in inner galaxy, diffuse background
  - Search for DM annihilation in subhalos
  - *complementary to morphology-based searches (e.g. hazes)*
- PLANCK : probe annihilation in cold early universe
  - look for effects of annihilation at the epoch of recombination, through CMB power spectrum.

A New Source of e^+e^- ...but what is it?

PAMELA satellite

Nature, 2009
(~1 citation/day)

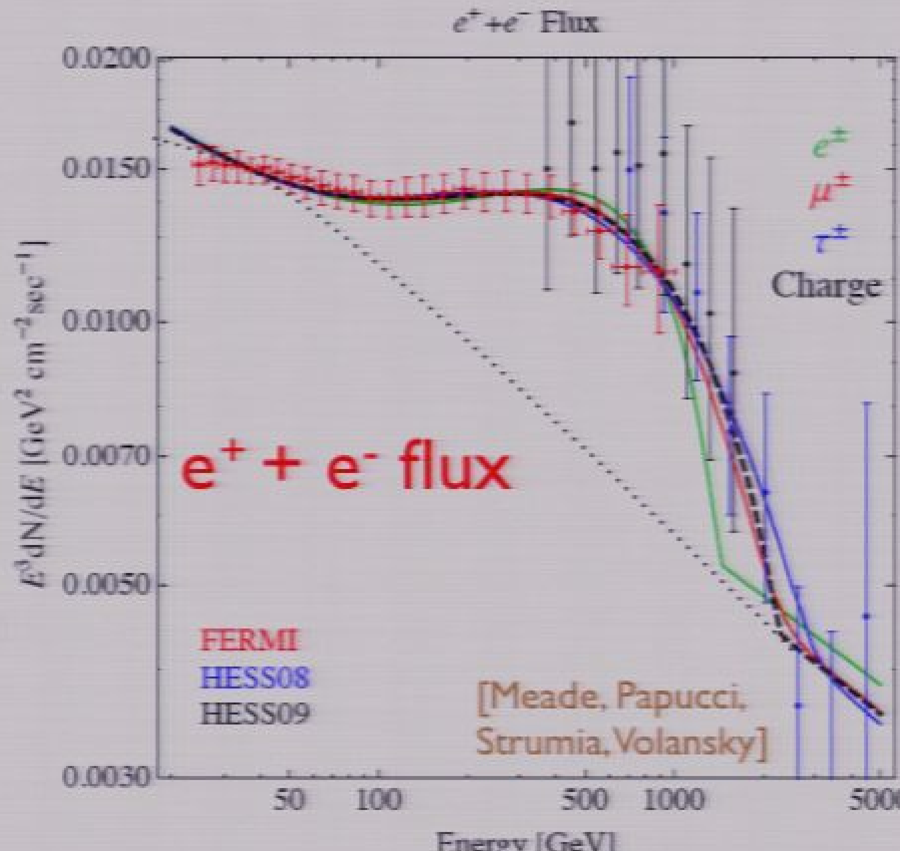




New e+ source

theory expectation

Fermi satellite, HESS



$e^+ + e^-$ flux

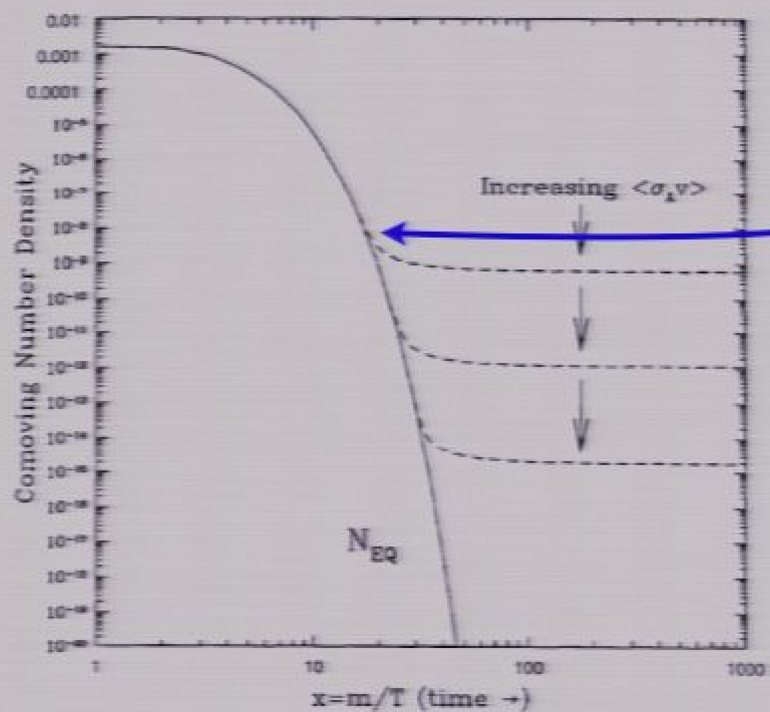
[Meade, Papucci, Strumia, Volansky]

$E_{max}(e+, e-) \sim M(DM)$

Need large annihilation cross-section to explain!

Dark Matter Annihilation Rates

What we "know" about dark matter annihilation rates comes from the thermal production story:



$\sigma v \sim 3\ 10^{-26}$ cm^3/s at v~1/3 c

Want $\sigma v \sim 10^{-23}$ cm^3/s in galaxy today ($v \sim 10^{-3}$ c)

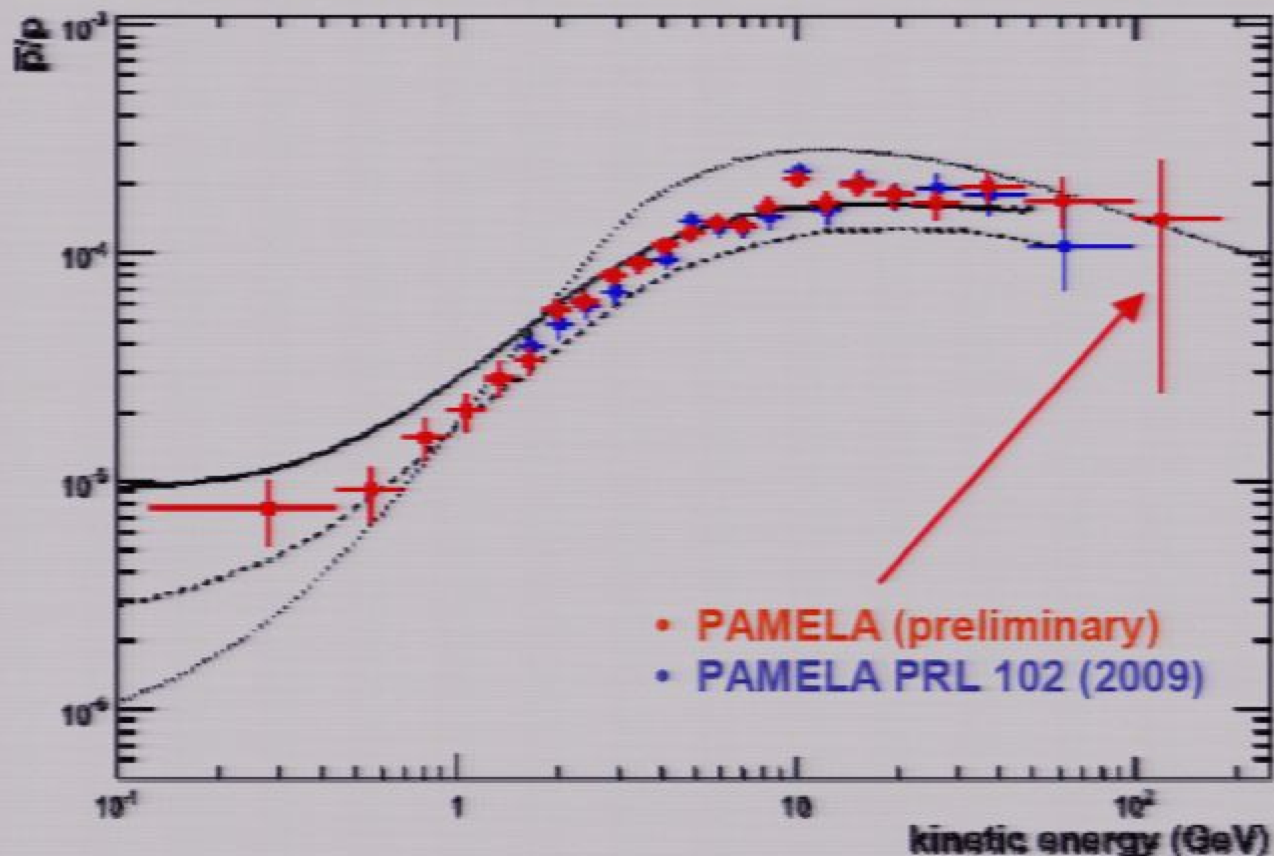
s-wave tree-level annihilation $\Rightarrow \sigma v \sim v^0$

Long-range attractive force enhances annihilation $\Rightarrow \sigma v \sim 1/v$

Not EM charged; new long-range force $\Rightarrow$ **new light particle** (scalar or vector) mediating that force, $m \lesssim 10^{-3} M_{DM}$

What about anti-protons?

Naive expectation: dark matter annihilates into ALL Standard Model particles including hadrons – should see anti-proton excess, as well.

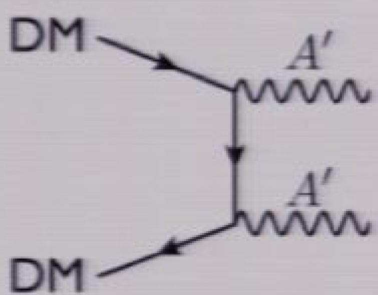


...why is there no anti-proton excess?

Consequences of a new force carrier, part 2

Considered a light force carrier to explain why σv is higher now (low velocity) than in early universe (high velocity)

If annihilation to this state (A′) dominates:



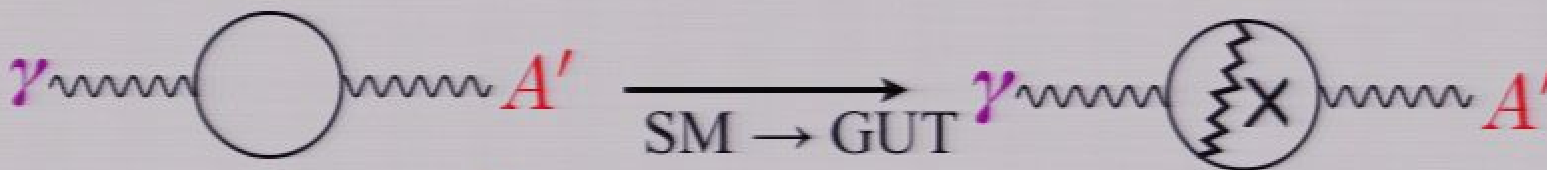
Observed annihilation products dictated by A′ couplings **and mass**

$$m_{A'} \lesssim 1 \text{ GeV} \Rightarrow A' \to \ell^+\ell^-, \pi^+\pi^-$$

[Arkani-Hamed, Finkbeiner, Slatyer, Weiner; Pospelov & Ritz]

Light Gauge Bosons?

Could an MeV–GeV-mass gauge boson be hidden under our noses? **YES! If coupling to Standard Model matter ≲10^{-2} e**



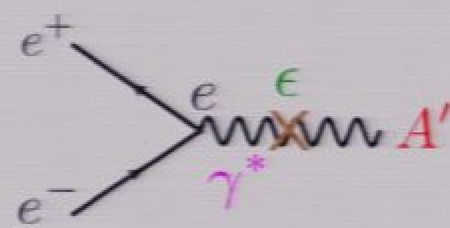
$\epsilon \sim 10^{-4} - 10^{-2}$

$\epsilon \sim 10^{-5} - 10^{-3}$

(ϵ generated by GUT-symmetry-breaking effects)

$$\Rightarrow \Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} \Rightarrow$$

[Holdom]



Supersymmetric generalization of this term generates

$m^2_{A'} \sim \epsilon M^2_W \sim \text{MeV}^2 - \text{GeV}^2$ [e.g. Cheung, Ruderman, Wang, Yavin; Katz, Sundrum; Morrissey, Poland, Zurek]

Mediates dark matter-nuclear scattering with ***parametrically*** same rate as the Z boson.

A General Theme

Two most exciting scenarios:

- Dark matter is intimately tied to new physics that solves puzzles of the Standard Model
  - SUSY Neutralino WIMP
  - QCD axion
  - anthropic WIMP models...
- Dark matter is a window on **completely new** physics

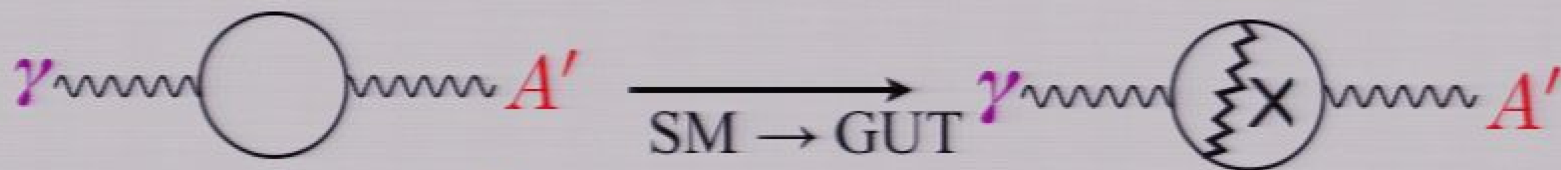
Electron Cosmic Ray data is first **positive indication** for 2nd case!

In either best-case scenario, lots of structure to understand ***from data***, and soon! Very different from limits, model→prediction exercises of the last ~20 years.

Looking in ***all*** relevant corners, combining results is key to figuring out how nature really works.

Light Gauge Bosons?

Could an MeV–GeV-mass gauge boson be hidden under our noses? **YES! If coupling to Standard Model matter ≲10^{-2} e**



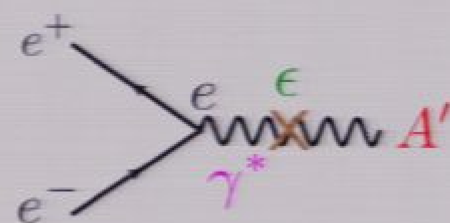
$\epsilon \sim 10^{-4} - 10^{-2}$

$\epsilon \sim 10^{-5} - 10^{-3}$

(ϵ generated by GUT-symmetry-breaking effects)

$$\Rightarrow \Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} \Rightarrow$$

[Holdom]



Supersymmetric generalization of this term generates

$m^2_{A'} \sim \epsilon M_W^2 \sim \mathrm{MeV}^2 - \mathrm{GeV}^2$ [e.g. Cheung, Ruderman, Wang, Yavin; Katz, Sundrum; Morrissey, Poland, Zurek]

Mediates dark matter-nuclear scattering with ***parametrically*** same rate as the Z boson.

A General Theme

Two most exciting scenarios:

- Dark matter is intimately tied to new physics that solves puzzles of the Standard Model
  - SUSY Neutralino WIMP
  - QCD axion
  - anthropic WIMP models...
- Dark matter is a window on **completely new** physics

Electron Cosmic Ray data is first **positive indication** for 2nd case!

In either best-case scenario, lots of structure to understand ***from data***, and soon! Very different from limits, model→prediction exercises of the last ~20 years.

Looking in ***all*** relevant corners, combining results is key to figuring out how nature really works.

A General Theme

Two most exciting scenarios:

- Dark matter is intimately tied to new physics that solves puzzles of the Standard Model
  - SUSY Neutralino WIMP
  - QCD axion
  - anthropic WIMP models...
- Dark matter is a window on **completely new** physics

Electron Cosmic Ray data is first **positive indication** for 2nd case!

In either best-case scenario, lots of structure to understand ***from data***, and soon! Very different from limits, model→prediction exercises of the last ~20 years.

Looking in ***all*** relevant corners, combining results is key to figuring out how nature really works.

Dark Forces

If dark matter is interacting with new gauge forces, how can we confirm their existence and unravel their structure?

- Structure of "dark sectors"
- Direct Production → Flavor factories; *e* fixed target; *p* fixed target; Tevatron/LHC
  - What's been done
  - Most promising searches to look forward to
- Exotic Astrophysical Searches!

Structure of “Dark Sectors”

Minimal:

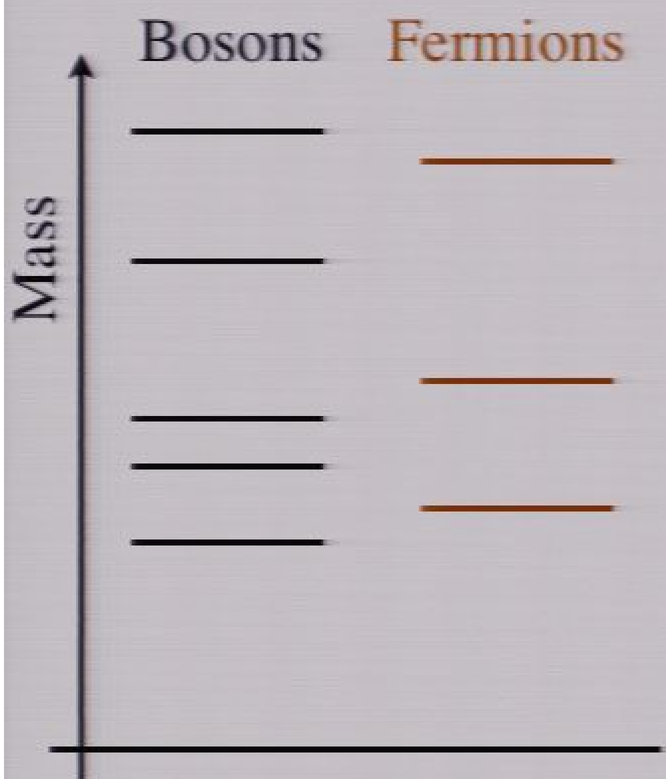
- Gauge boson A'
- Higgs boson h_D

Structure of "Dark Sectors"

Generic:

- Gauge boson(s) A' ($W_{i,D}$)
- Higgs boson(s) hD ($h_{i,D}, a_{i,D}$)
- Fermions ψ_i

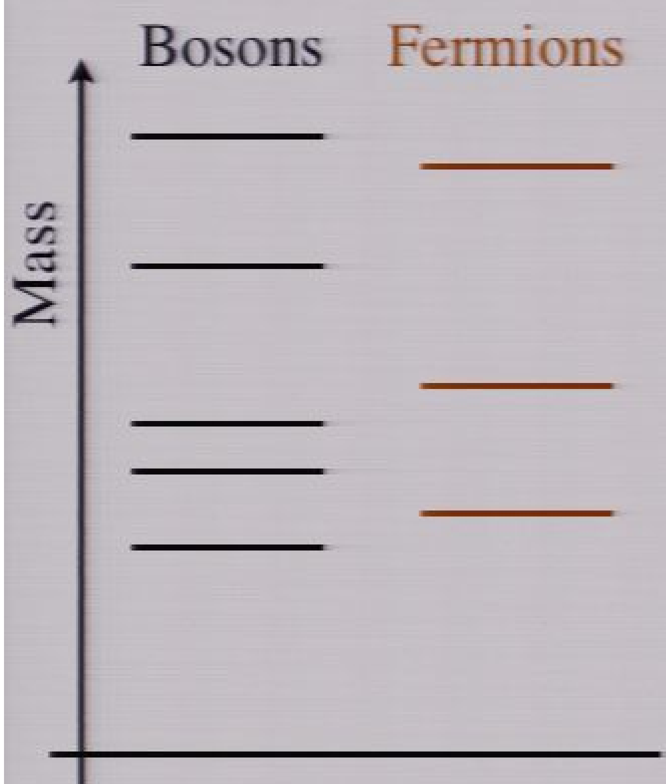
$$\mathcal{L} = \overbrace{\mathcal{L}_{dark}}^{\mathcal{O}(1)} + \overbrace{\mathcal{L}_{SM}}^{\mathcal{O}(1)} + \overbrace{\mathcal{L}_{mix}}^{\mathcal{O}(\epsilon)}$$



Structure of "Dark Sectors"

Generic:

- Gauge boson(s) A' ($W_{i,D}$)
- Higgs boson(s) hD ($h_{i,D}, a_{i,D}$)
- Fermions ψ_i



$$\mathcal{L} = \overbrace{\mathcal{L}_{dark}}^{\mathcal{O}(1)} + \overbrace{\mathcal{L}_{SM}}^{\mathcal{O}(1)} + \overbrace{\mathcal{L}_{mix}}^{\mathcal{O}(\epsilon)}$$

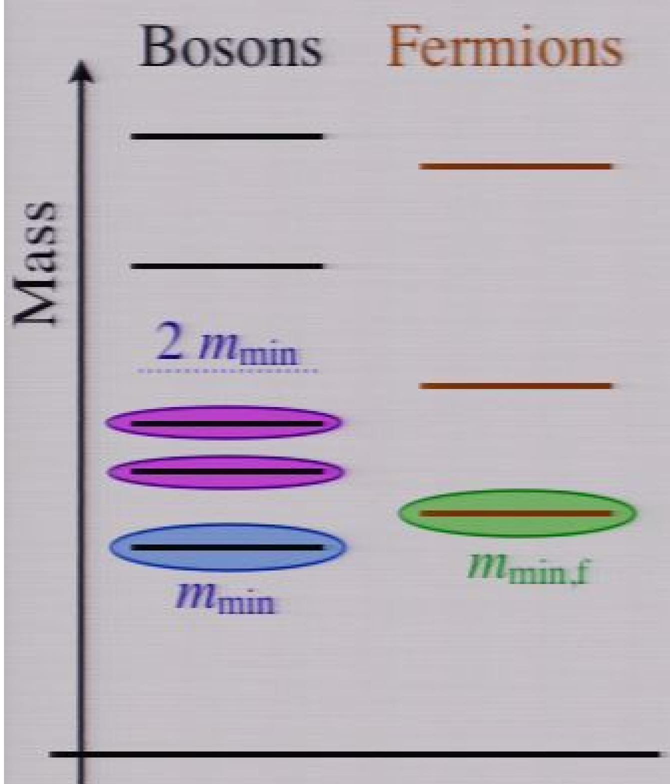
In $\epsilon \to 0$ limit (no coupling to SM), several kinds of particle are stable:

Structure of "Dark Sectors"

Generic:

- Gauge boson(s) A' ($W_{i,D}$)
- Higgs boson(s) hD ($h_{i,D}, a_{i,D}$)
- Fermions ψ_i

$$\mathcal{L} = \overbrace{\mathcal{L}_{dark}}^{\mathcal{O}(1)} + \overbrace{\mathcal{L}_{SM}}^{\mathcal{O}(1)} + \overbrace{\mathcal{L}_{mix}}^{\mathcal{O}(\epsilon)}$$



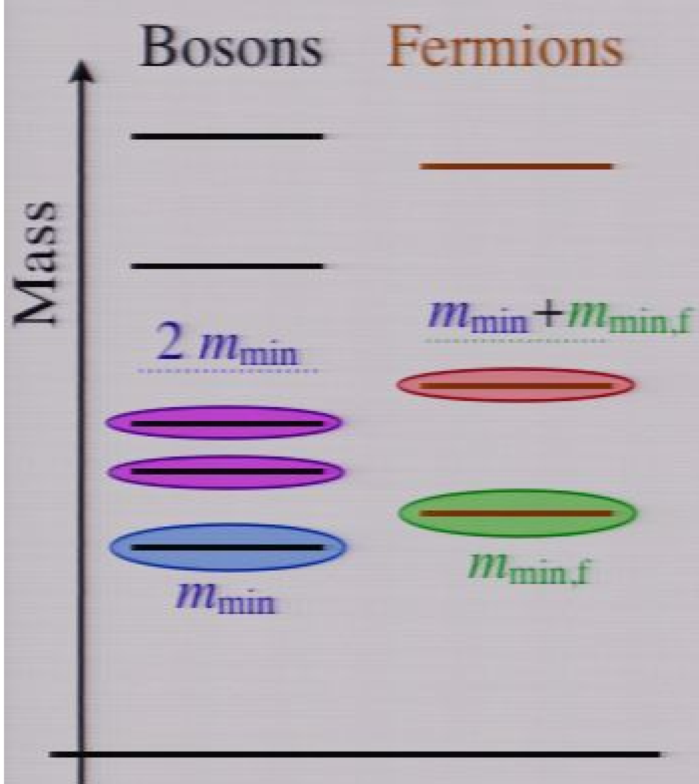
In $\epsilon \to 0$ limit (no coupling to SM), several kinds of particle are stable:

- Lightest particle
- Lightest fermion (protected by fermion number)
- All bosons with $m > 2\, m_{\text{min}}$ (protected by energy conservation)

Structure of "Dark Sectors"

Generic:

- Gauge boson(s) A′ ($W_{i,D}$)
- Higgs boson(s) hD ($h_{i,D}, a_{i,D}$)
- Fermions ψ_i



$$\mathcal{L} = \overbrace{\mathcal{L}_{dark}}^{\mathcal{O}(1)} + \overbrace{\mathcal{L}_{SM}}^{\mathcal{O}(1)} + \overbrace{\mathcal{L}_{mix}}^{\mathcal{O}(\epsilon)}$$

In $\epsilon \rightarrow 0$ limit (no coupling to SM), several kinds of particle are stable:

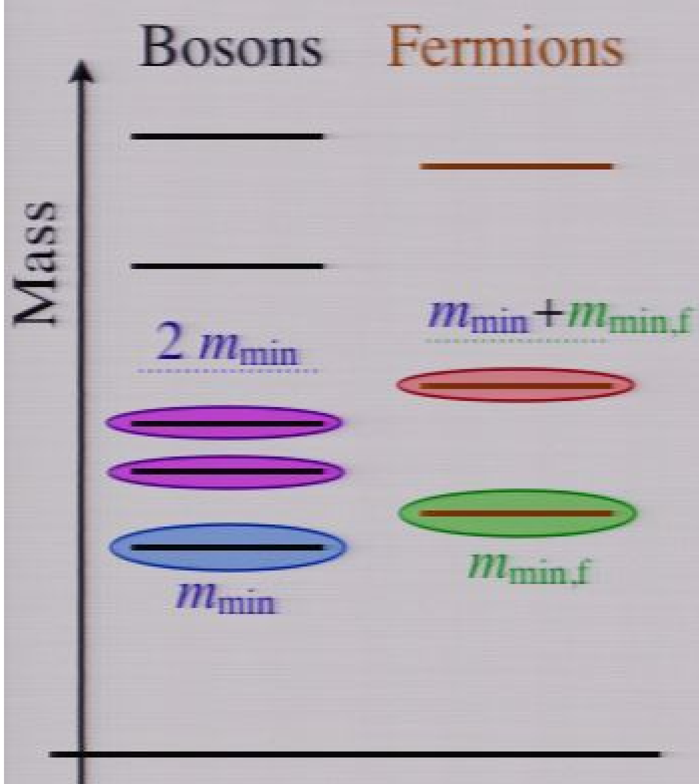
- Lightest particle
- Lightest fermion (protected by fermion number)
- All bosons with $m>2\, m_{min}$ (protected by energy conservation)
- All fermions with $m>m_{min}+m_{min,f}$ (E conservation **and** fermion no.)
- Particles stabilized by dark-sector flavor/discrete symmetries

Structure of "Dark Sectors"

Generic:

- Gauge boson(s) A′ ($W_{i,D}$)
- Higgs boson(s) hD ($h_{i,D}, a_{i,D}$)
- Fermions ψ_i

$$\mathcal{L} = \overbrace{\mathcal{L}_{dark}}^{\mathcal{O}(1)} + \overbrace{\mathcal{L}_{SM}}^{\mathcal{O}(1)} + \overbrace{\mathcal{L}_{mix}}^{\mathcal{O}(\epsilon)}$$



In $\epsilon \to 0$ limit (no coupling to SM), several kinds of particle are stable:

- Lightest particle
- Lightest fermion (protected by fermion number)
- All bosons with $m>2\,m_{min}$ (protected by energy conservation)
- All fermions with $m>m_{min}+m_{min,f}$ (E conservation **and** fermion no.)
- Particles stabilized by dark-sector flavor/discrete symmetries

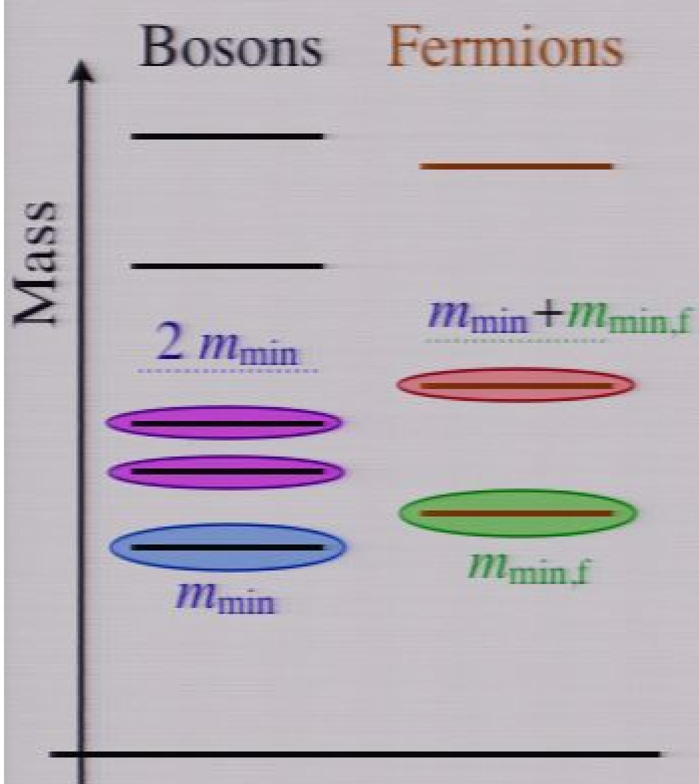
Heavier dark sector particles decay (quickly) to these "metastable" species.

⇒ Decays of the metastable species (lifetime $\propto \epsilon^{-p}$) control **all** decays into Standard Model

Structure of "Dark Sectors": Decay Lifetimes

Lifetimes depend on quantum numbers, and on $\mathcal{L}_{mix}$ but not sensitive to details of $\mathcal{L}_{dark}$!

e.g. for $\mathcal{L}_{mix} = \frac{\epsilon}{2} F_\mu F_D^{\mu\nu}$



Lightest

$< m_{\text{thresh}}$

Vector

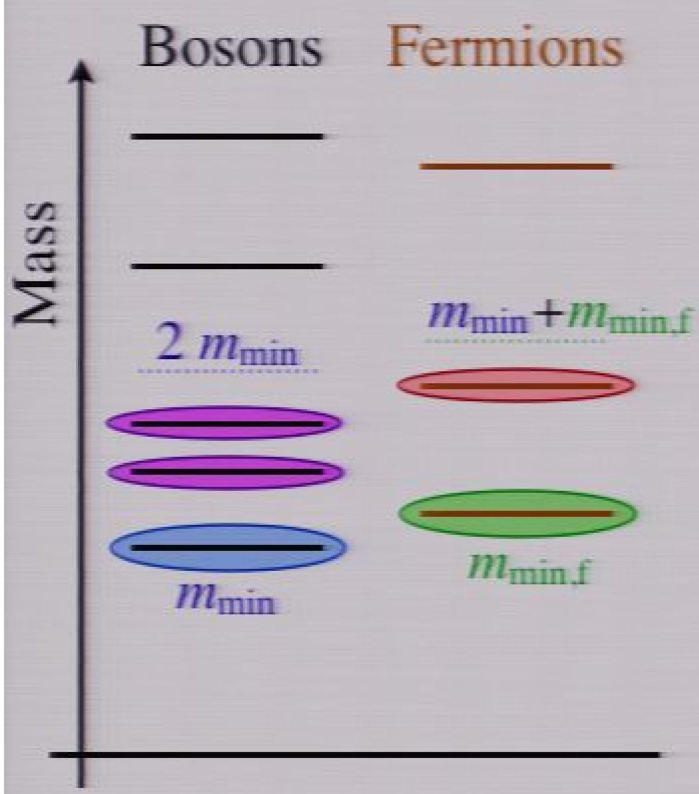
Fermion

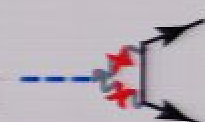
Scalar

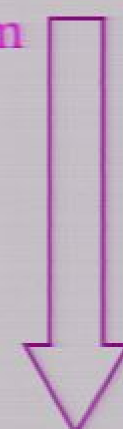
Structure of "Dark Sectors": Decay Lifetimes

Lifetimes depend on quantum numbers, and on $\mathcal{L}_{mix}$ but not sensitive to details of $\mathcal{L}_{dark}$!

e.g. for $\mathcal{L}_{mix} = \frac{\epsilon}{2} F_\mu F_D^{\mu\nu}$



	Lightest		$< m_{\text{thresh}}$
Vector	$c\tau = \frac{3}{m\alpha\epsilon^2}$ $c\tau \sim 0.2\ \mu m$		$\frac{128\pi}{m\alpha\alpha_D\epsilon^2}$ $c\tau \sim 1$ cm 
Fermion	**stable** ($\mathcal{L}_{mix}$ respects dark fermion no.)		
Scalar	$\frac{\pi^2}{2m\alpha_D\alpha^2\epsilon^4}$ $c\tau \sim 100$ km		



For example:
$\alpha_D = \alpha$, $\epsilon = 10^{-3}$, $m = 250$ MeV

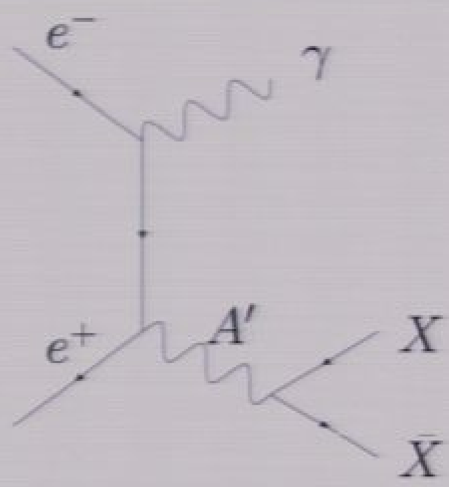
Need to look at wide variety of final states, distance scales!!

If dark matter is interacting with new gauge forces, how can we confirm their existence and unravel their structure?

- Structure of "dark sectors"
- Direct Production → Flavor factories; *e* fixed target; *p* fixed target; Tevatron/LHC
  - What's been done
  - Most promising searches to look forward to
- Exotic Astrophysical Searches!

Flavor Factories — Direct Production

1)



$$\sigma \approx \frac{2\pi\alpha^2\epsilon^2}{E_{cm}^2}; N_{A'} \propto \frac{\text{luminosity}}{E_{cm}^2}$$

$\Rightarrow$ tremendous advantage to high-intensity, lower-energy colliders.

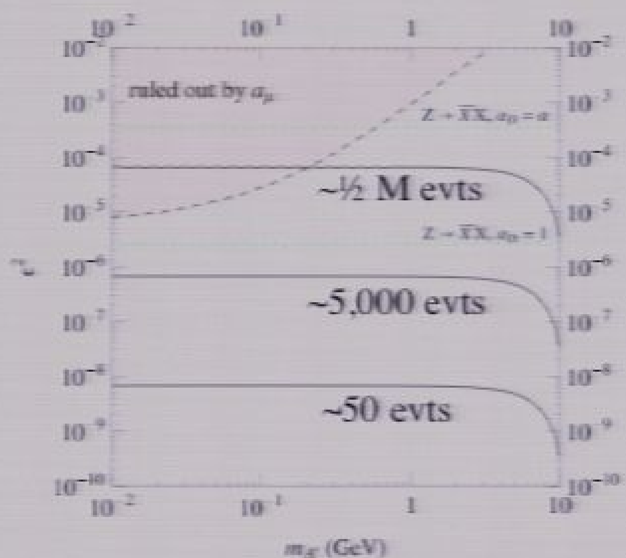
B-factories

– Operate at E_{cm}~10 GeV

– Highest-luminosity colliding beams

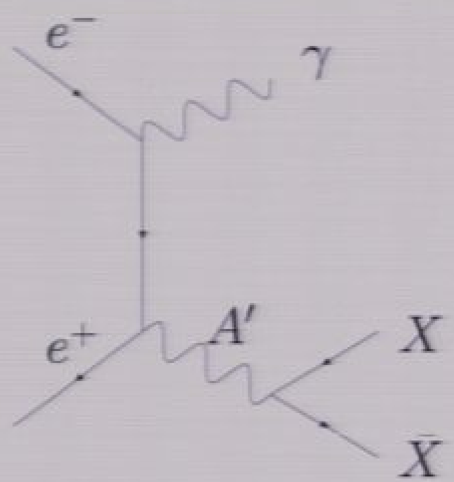
– 10^5 more production than LEP!

Lower-luminosity and -energy colliders also competitive: KLOE (Phi factory), upcoming BES-3

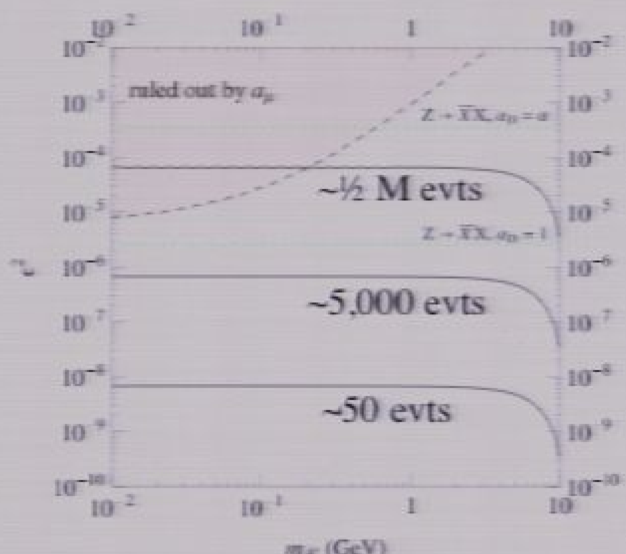


Flavor Factories — Direct Production

1)



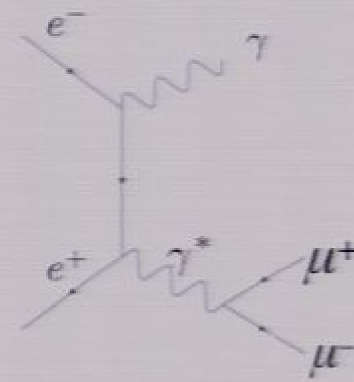
$$\sigma \approx \frac{2\pi\alpha^2\epsilon^2}{E_{cm}^2};$$



<u>Minimal decay:</u>

A′→$\mu^+ \mu^-$ (or other SM)

Large background:



$$S/\sqrt{B} \propto \epsilon^2 \sqrt{\text{luminosity}}$$

Sensitivity: $\epsilon^2 \sim 10^{-6}$

<u>More general decays</u> (or other production modes)

A′→$X_D\, Y_D$ (X, Y non-Abelian gauge bosons or other states)

multiple leptons, perhaps displaced vertices
⇒ low background

$$S \propto \epsilon^2 \times \text{luminosity}$$

ϵ^2 as low as 10^{-8}–10^{-9} discoverable!

Also for more general production

Flavor Factories

Two completed Searches at BaBar
(both simple and complex final states)

Many other modes being studied at
BaBar, Belle, KLOE, BES

Many searches stimulated, broadened
at SLAC dark forces workshop, 2009.

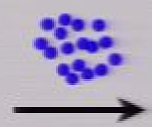
See conference website for details

http://www-conf.slac.stanford.edu/darkforces2009/

[see Batell, Pospelov, Ritz; Essig, Schuster, NT; Reece and Wang]

Advantages of Fixed Target Direct Production

	Fixed-Target	e^+e^-
LUMINOSITY	10^{11} e^- → ~10^{23} atoms in target	10^{11} e^- → ← 10^{11} e^+



N(hard scatter) ~ 0.01 – 1 *per electron*

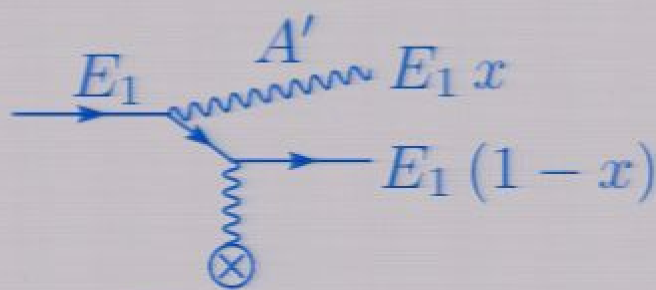
N(hard scatter) ~ 1 *per crossing*

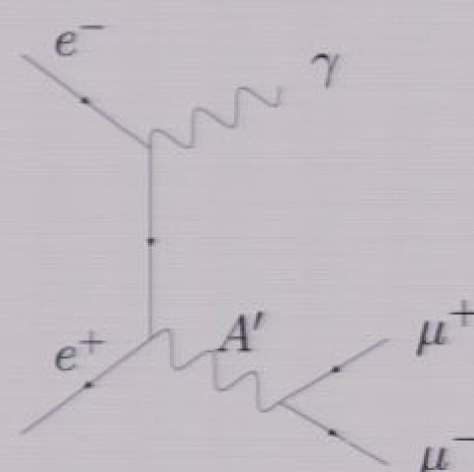
O(few) ab^{-1} per day | O(few) ab^{-1} per decade

CROSS-SECTION

– Scales as A′ mass, not beam energy

– Coherent scattering from nucleus





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

$$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$$

Fixed Target Territory

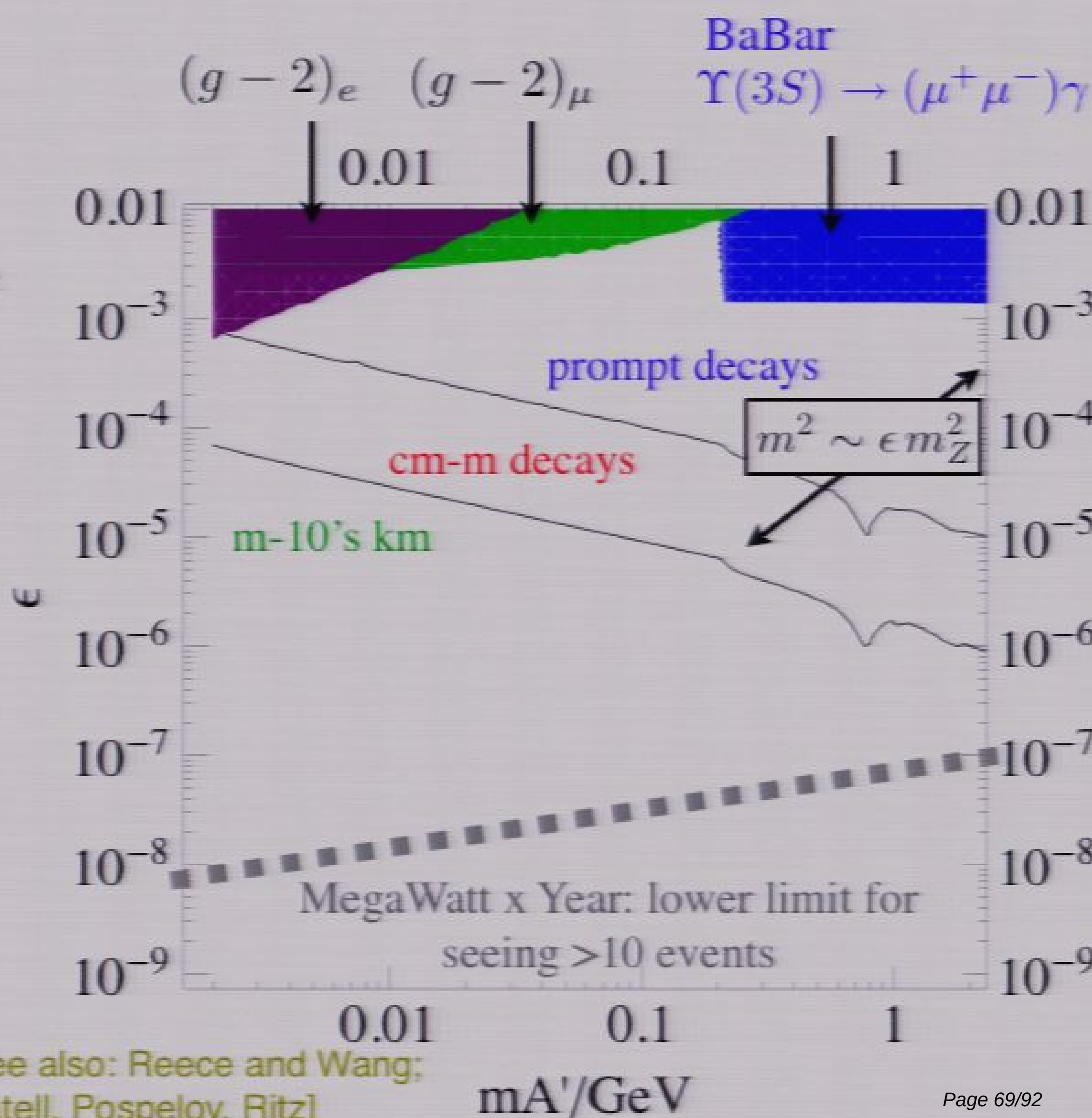
Direct Production

- Lifetime

$$\gamma c\tau \approx 1\ \text{mm}\,(\gamma/10)\left(10^{-4}/\epsilon\right)^2 \times (100\ \text{MeV}/m_{A'})$$

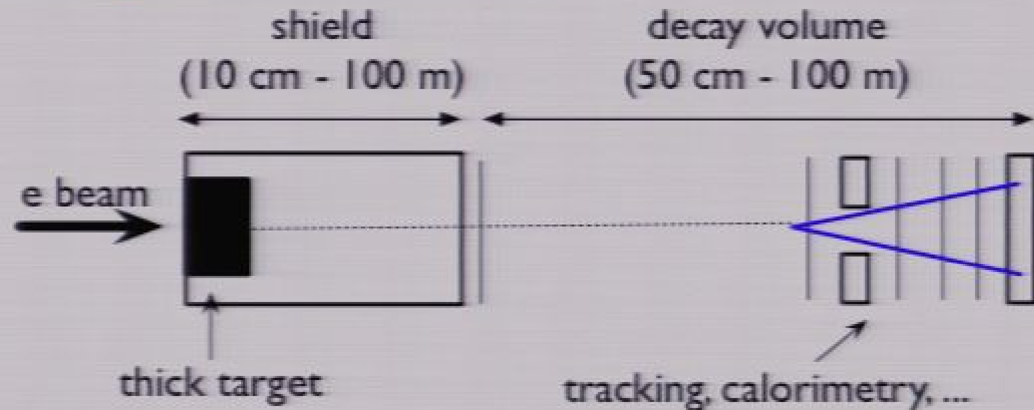
varies over 15 decades

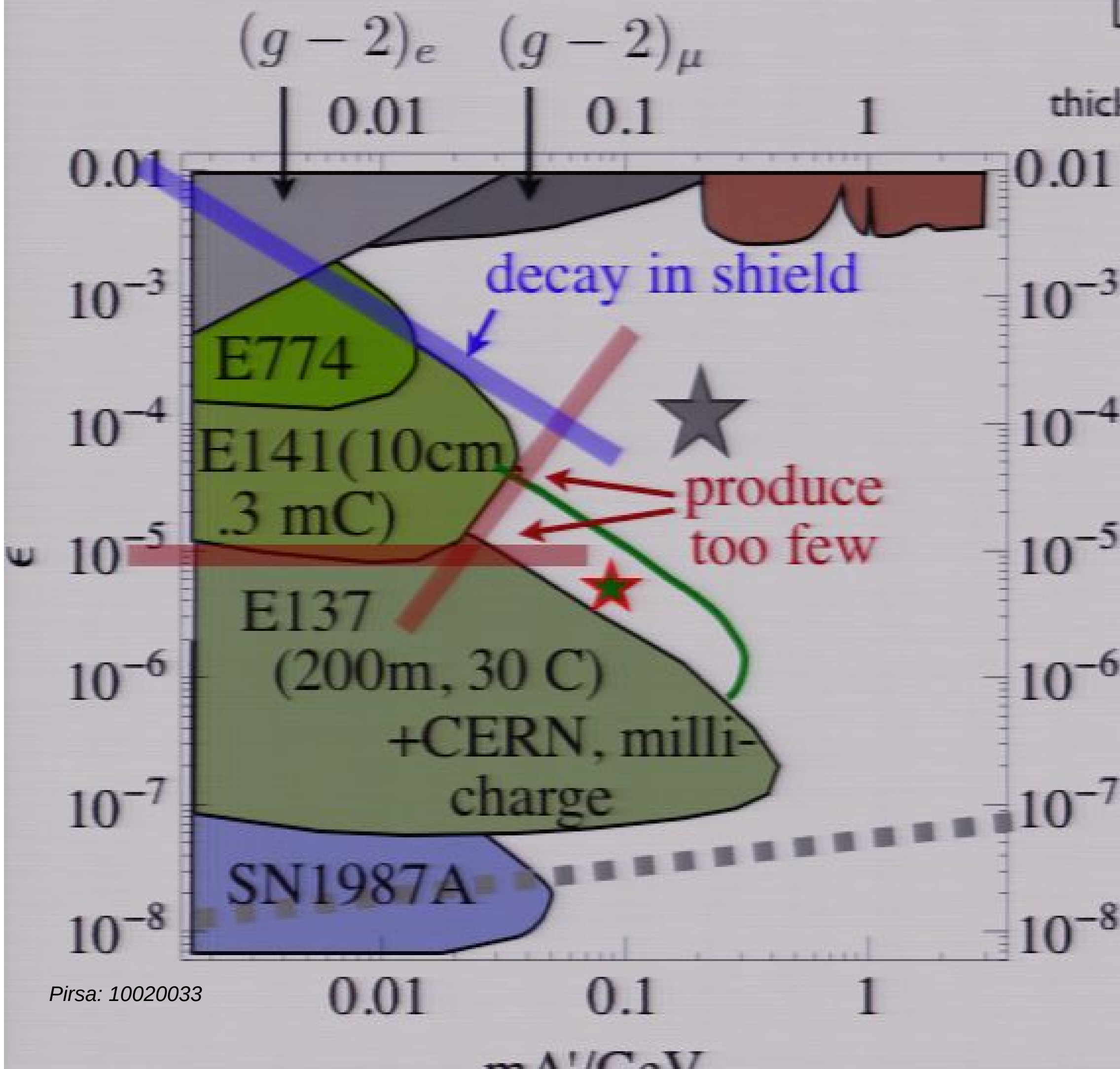
- Kinematics depends on mass
- Multiple detectors needed



[see also: Reece and Wang; Batell, Pospelov, Ritz]

Limits from Beam-Dump Experiments





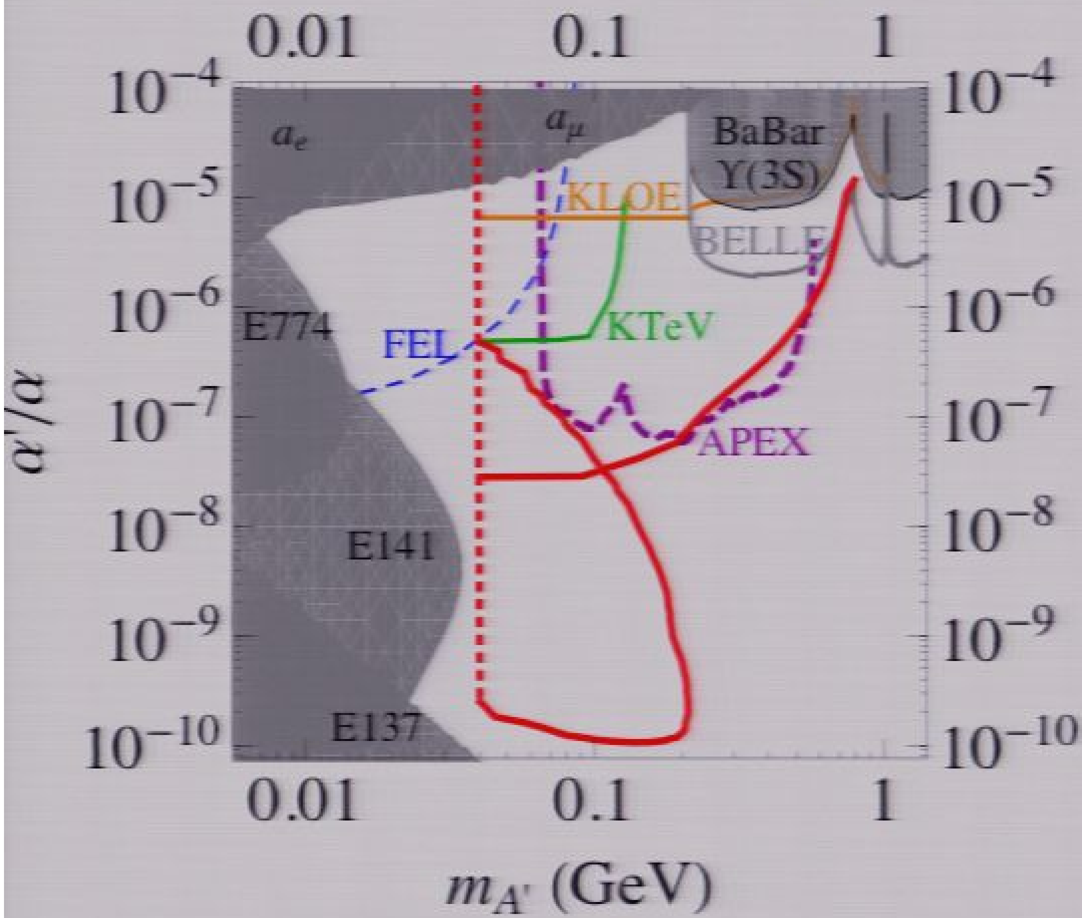
★ Key but challenging region

- ϵ too low for B-factories and precision QED
- Decays too prompt for beam dump

★ potential sensitivity of low-power beam dump (100 nA for few months)

Enormous potential for new sensitivity!

Experiments under development for next few years:



Significant new reach possible through search for small, narrow mass peaks (APEX and FEL) and vertexing.

– can explore all parameter space below 150 MeV

– significant new range to ~500 MeV!

– starting point for future designs with higher-mass coverage

Only at a few nuclear physics laboratories in the world!

– Jefferson Lab, Virginia (≤6 GeV)

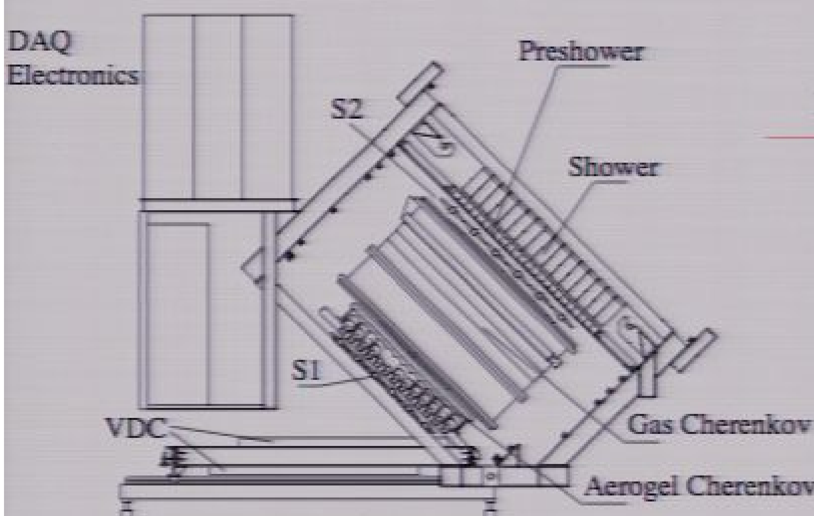
– Mainz Microtron (≤1.5 GeV)

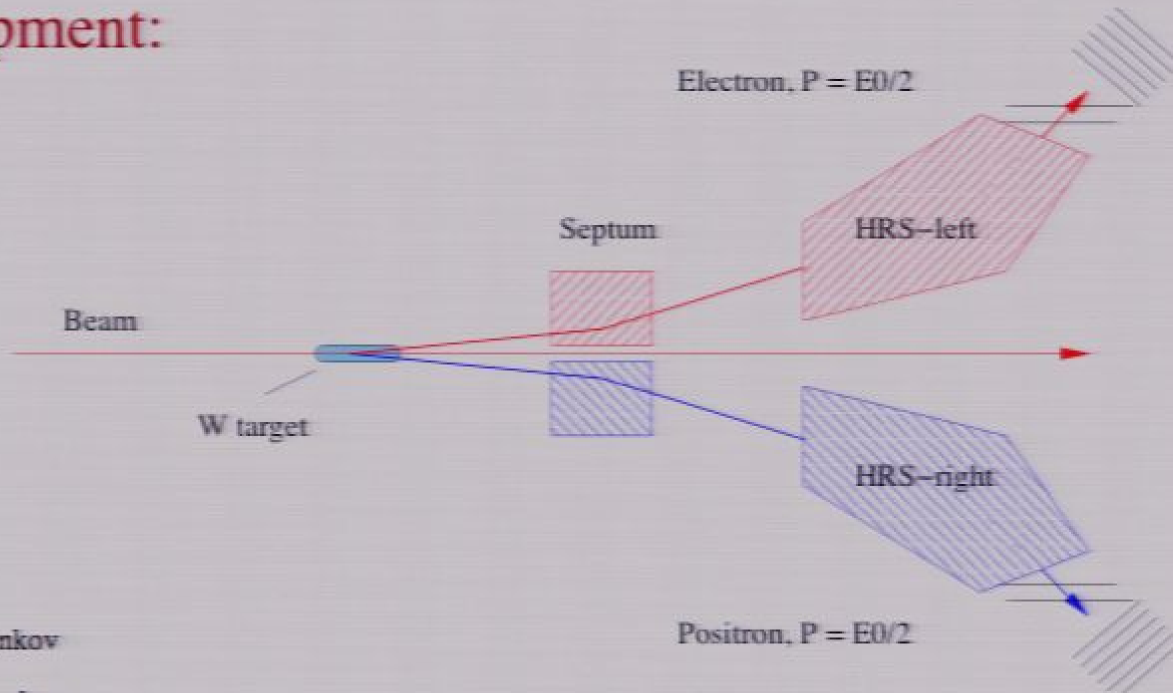
– Lund (100's MeV)

APEX

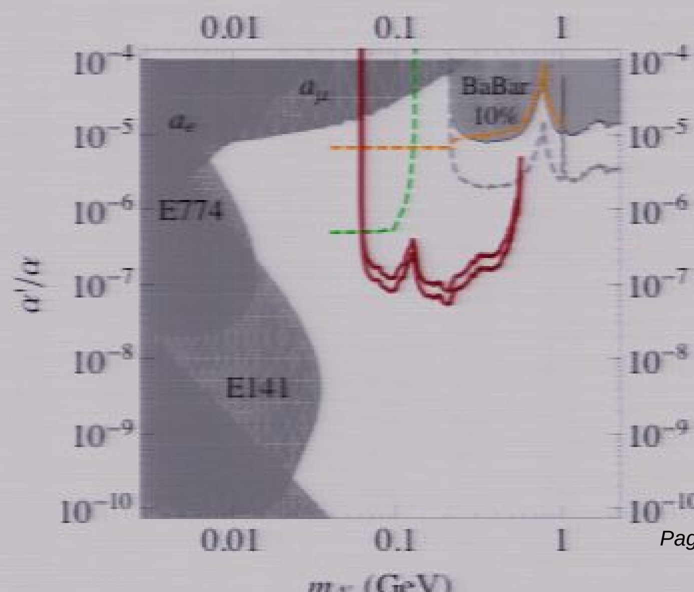
Direct Production

Use *existing*, *installed* equipment: precision spectrometers in Jefferson Lab (Hall A)





1-4.4 GeV beam, 75 μA on target



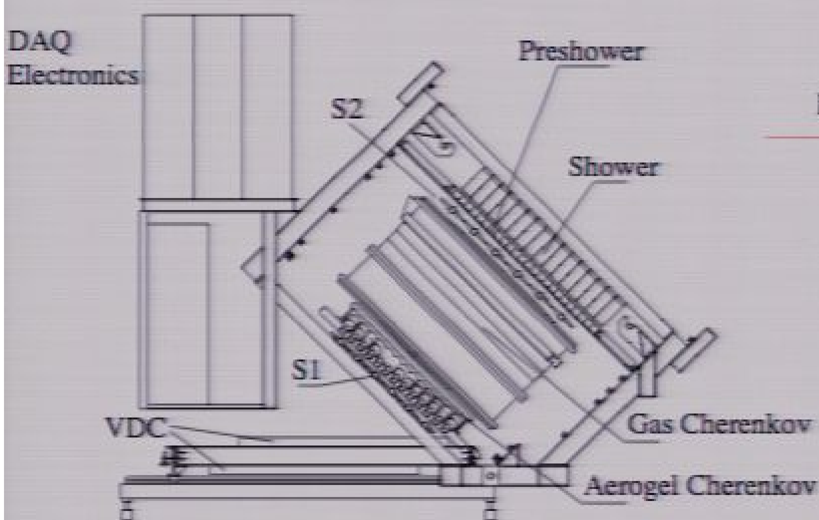
Spokespeople R. Essig, P. Schuster, NT, B. Wojtsekowsi, with group of ~40 collaborators at JLab, SLAC, many universities.

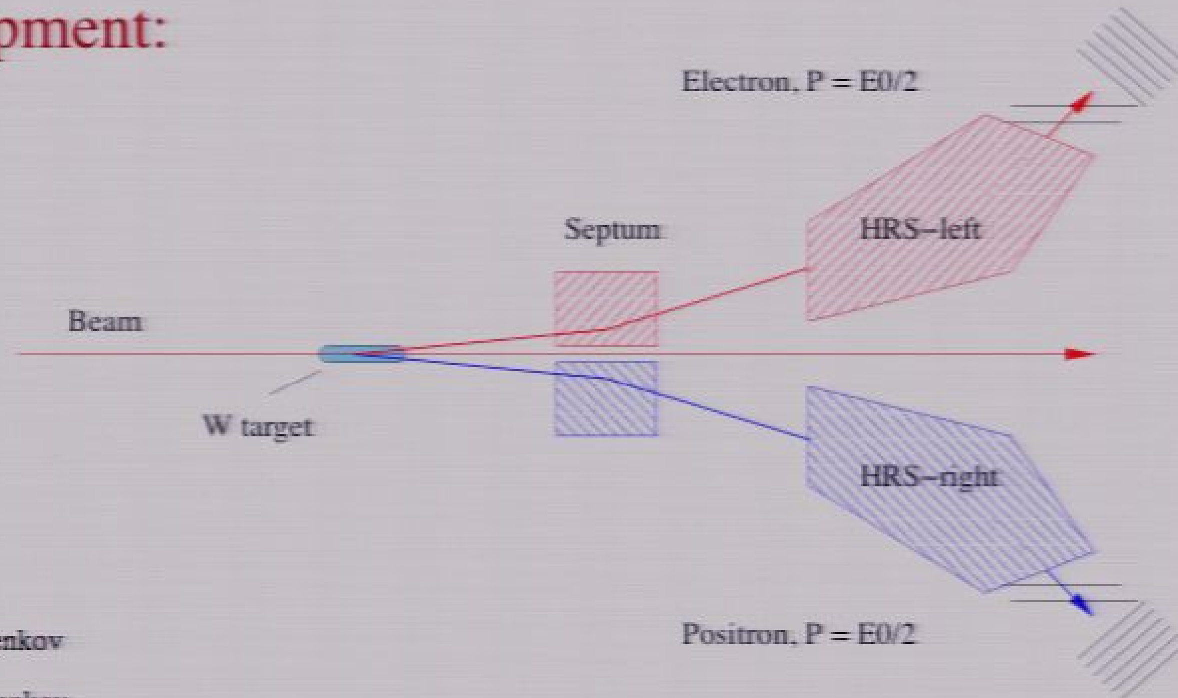
If dark matter is interacting with new gauge forces, how can we confirm their existence and unravel their structure?

- Structure of "dark sectors"
- Direct Production
  - What's been done
  - Most promising searches to look forward to
  - → Flavor factories
  - → e fixed target
  - → p fixed target
  - → Tevatron/LHC
- Exotic Astrophysical Searches!

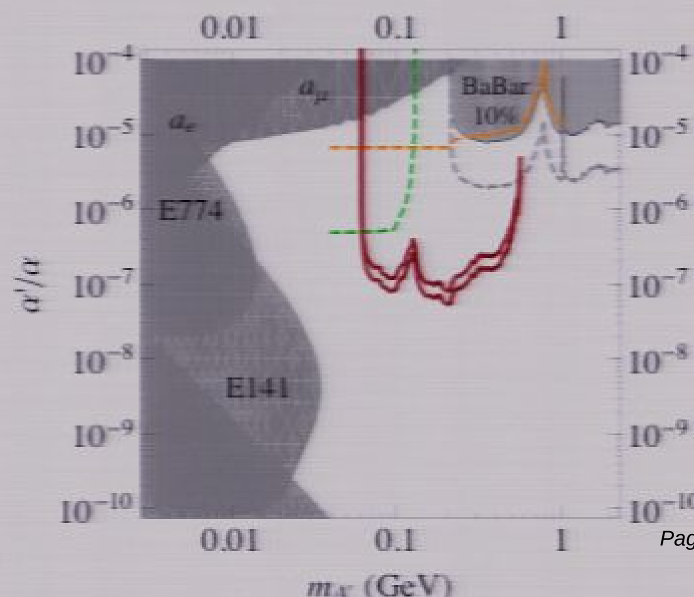
APEX

Use *existing*, *installed* equipment: precision spectrometers in Jefferson Lab (Hall A)





1-4.4 GeV beam, 75 μA on target



Spokespeople R. Essig, P. Schuster, NT, B. Wojtsekowsi, with group of ~40 collaborators at JLab, SLAC, many universities.

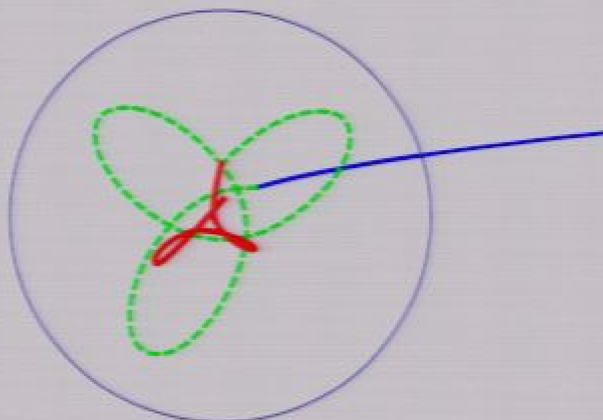
If dark matter is interacting with new gauge forces, how can we confirm their existence and unravel their structure?

- Structure of “dark sectors”
- Direct Production → Flavor factories; *e* fixed target; *p* fixed target; Tevatron/LHC
  - What’s been done
  - Most promising searches to look forward to
- Exotic Astrophysical Searches!

Dark Matter Annihilation Signals from the Sun

The sun as a **very big direct dark matter detector**

- Dark Matter can become gravitationally bound when it scatters off nuclei in the sun. [Silk, Olive, Srednicki; Press, Spergel]
- A good inelastic DM detector:
  - Contains heavy elements
  - Infalling particle accelerated by sun's gravity ⇒ above scattering threshold

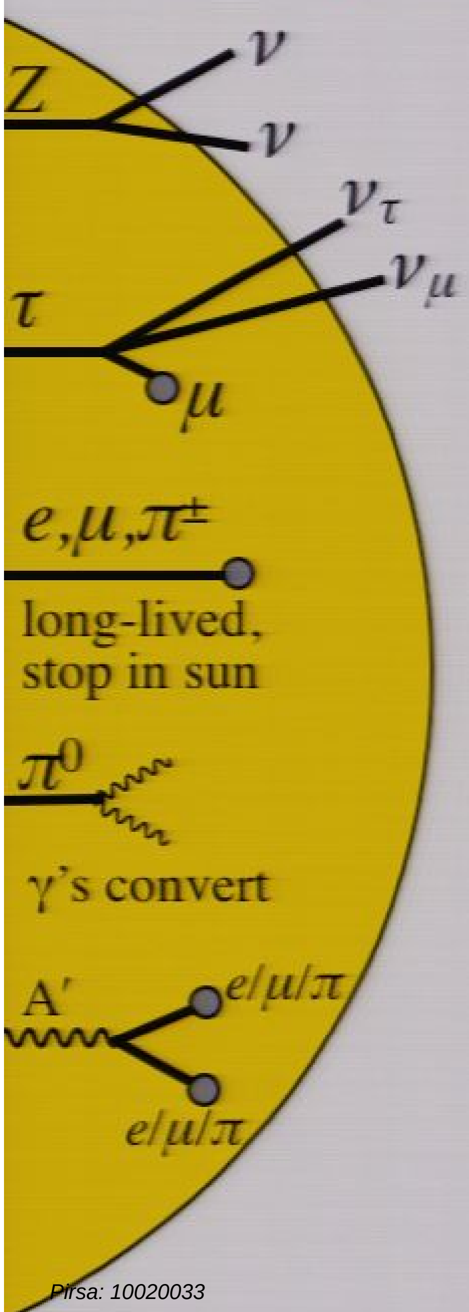


  - DAMA ⇒ Out of 1000 DM particle impinging on sun, one gets bound.

⇒ 10^{24-25} annihilations/second ⇒ 3/m^2/sec at Earth

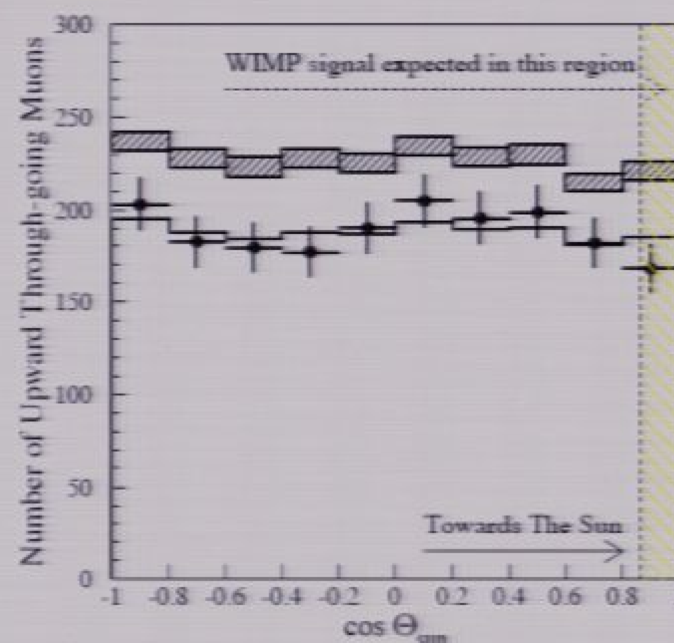
[Tucker-Smith and Weiner; Menon, Morris, Pierce, Weiner; Nussinov, Wang, Yavin; Shu, Yin, Zhu]

Searching for Dark Matter in the Sun



SuperK bounds on annihilation into final states that produce neutrinos are 100x lower. [Tucker-Smith and Weiner; Menon, Morris, Pierce, Weiner; Nussinov, Wang, Yavin; Shu, Yin, Zhu]

(stringent constraint on inelastic dark matter coupled to Z)

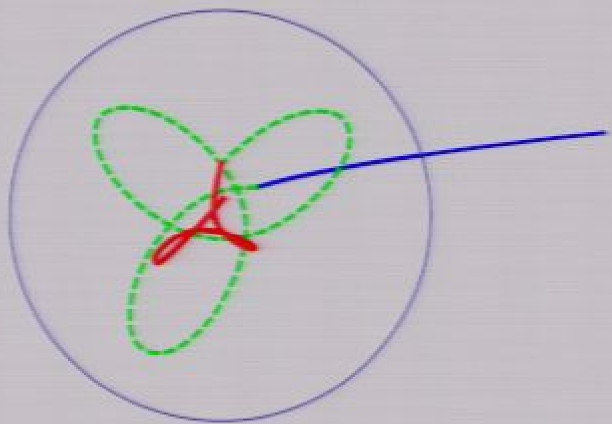


Does **not** apply to annihilation into light A′

Dark Matter Annihilation Signals from the Sun

The sun as a **very big direct dark matter detector**

- Dark Matter can become gravitationally bound when it scatters off nuclei in the sun. [Silk, Olive, Srednicki; Press, Spergel]

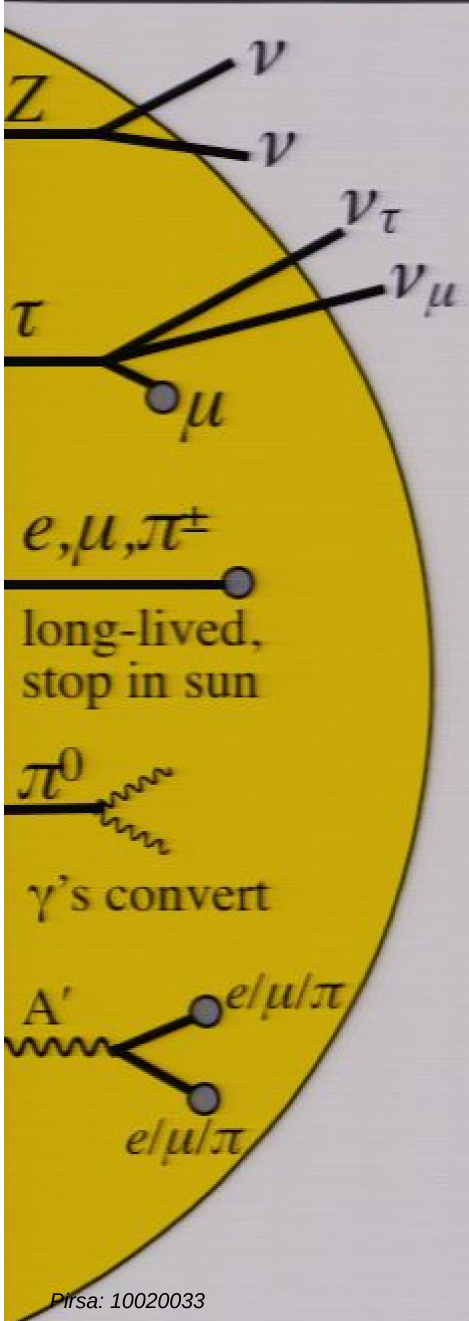


- A good inelastic DM detector:
  - Contains heavy elements
  - Infalling particle accelerated by sun's gravity ⇒ above scattering threshold
  - DAMA ⇒ Out of 1000 DM particle impinging on sun, one gets bound.

⇒ 10^{24-25} annihilations/second ⇒ $3/\text{m}^2/\text{sec}$ at Earth

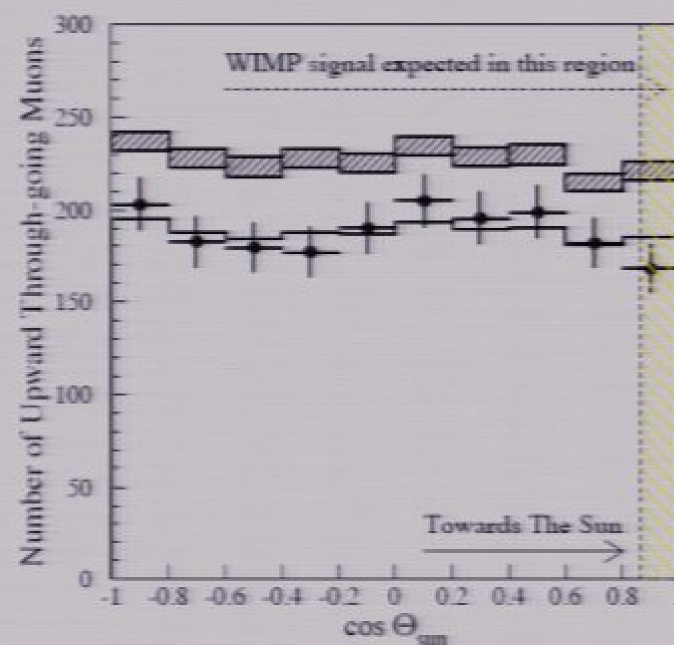
[Tucker-Smith and Weiner; Menon, Morris, Pierce, Weiner; Nussinov, Wang, Yavin; Shu, Yin, Zhu]

Searching for Dark Matter in the Sun



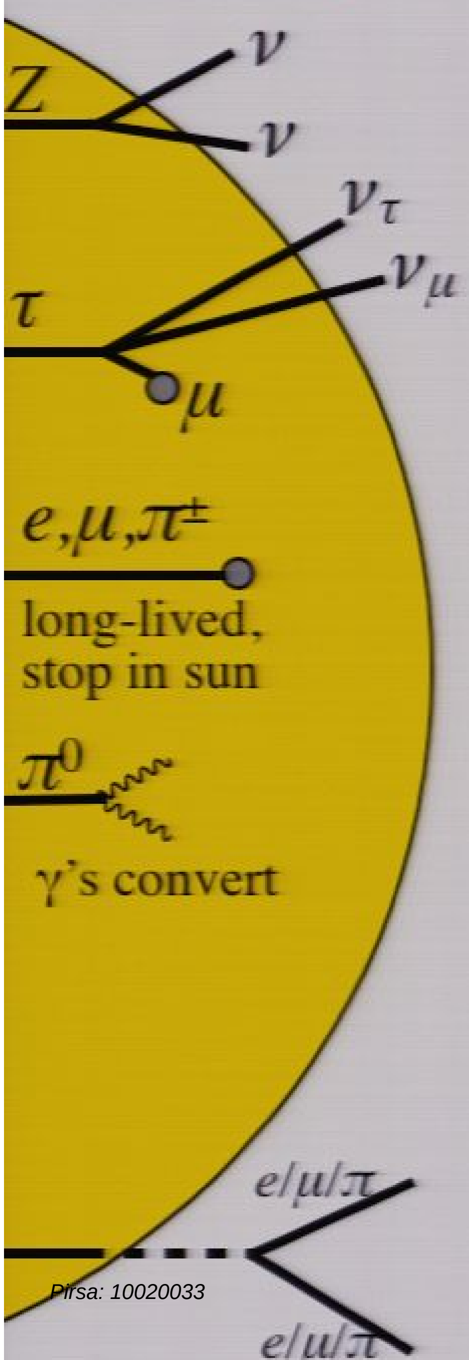
SuperK bounds on annihilation into final states that produce neutrinos are 100x lower. [Tucker-Smith and Weiner; Menon, Morris, Pierce, Weiner; Nussinov, Wang, Yavin; Shu, Yin, Zhu]

(stringent constraint on inelastic dark matter coupled to Z)



Does **not** apply to annihilation into light A′

Searching for Dark Matter in the Sun



The sun is **also** a giant beam-dump experiment:

Long-lived products of dark matter annihilation escape the sun:

- dark-sector higgs
- exotics with dimension-5 GUT decays

⇒ Solar source of hard e^+e^-?

$$\frac{10^{24}}{\text{second}} \times \frac{1}{4\pi \times 1\text{AU}^2} \sim 3/\text{m}^2/\text{sec}$$

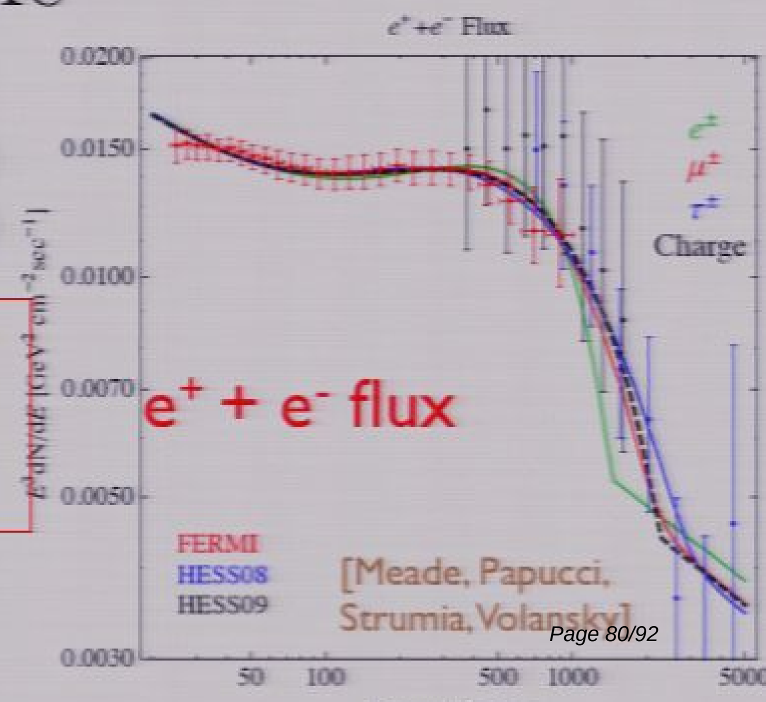
Fermi total flux

$0.08/\text{m}^2/\text{s}$ (E>100 GeV)

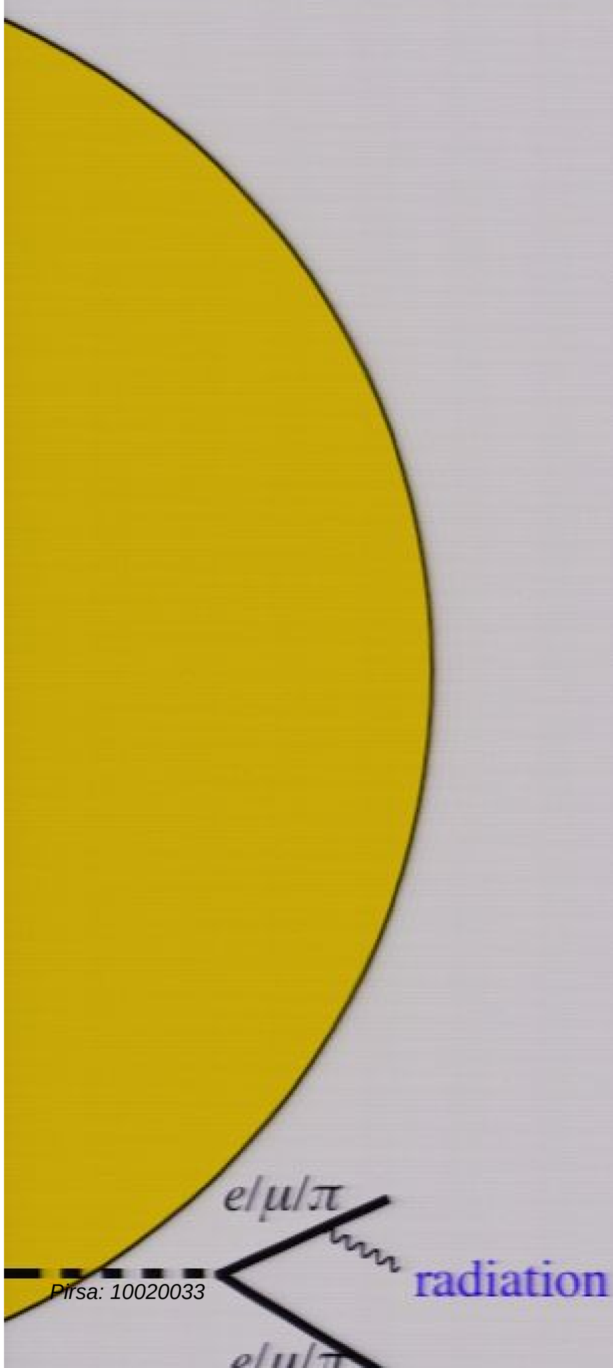
$0.002/\text{m}^2/\text{s}$ (E>500 GeV)

Can annihilation in the Sun be responsible for Fermi excess?

[Schuster, NT, Yavin, Weiner]



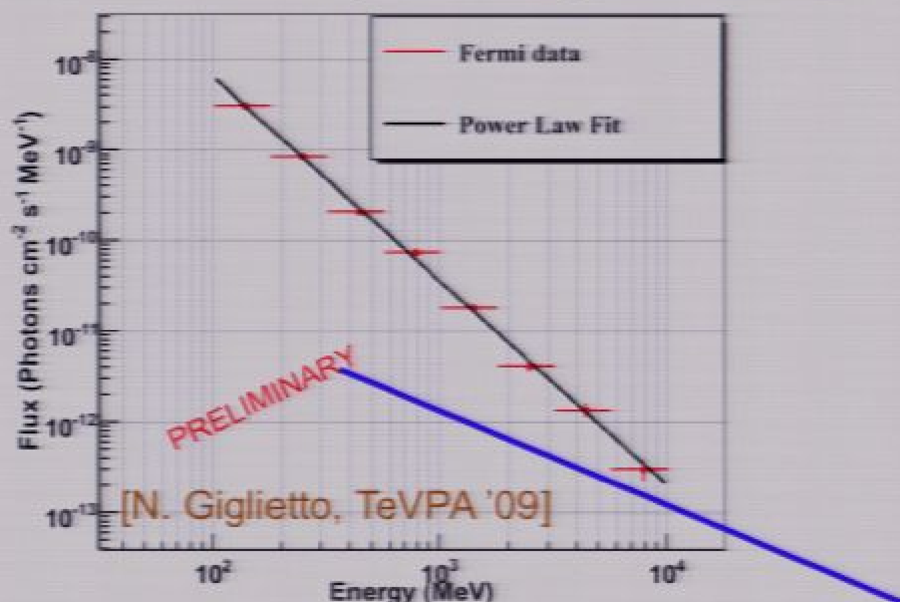
Photons/Electrons from DM Annihilation in the Sun?



Radiated photons:
- Spectrum ~ $1/E$
- "solar albedo" background ~ $1/E^2$

Inverse Compton scattering of sunlight
Cosmic ray nuclear interactions

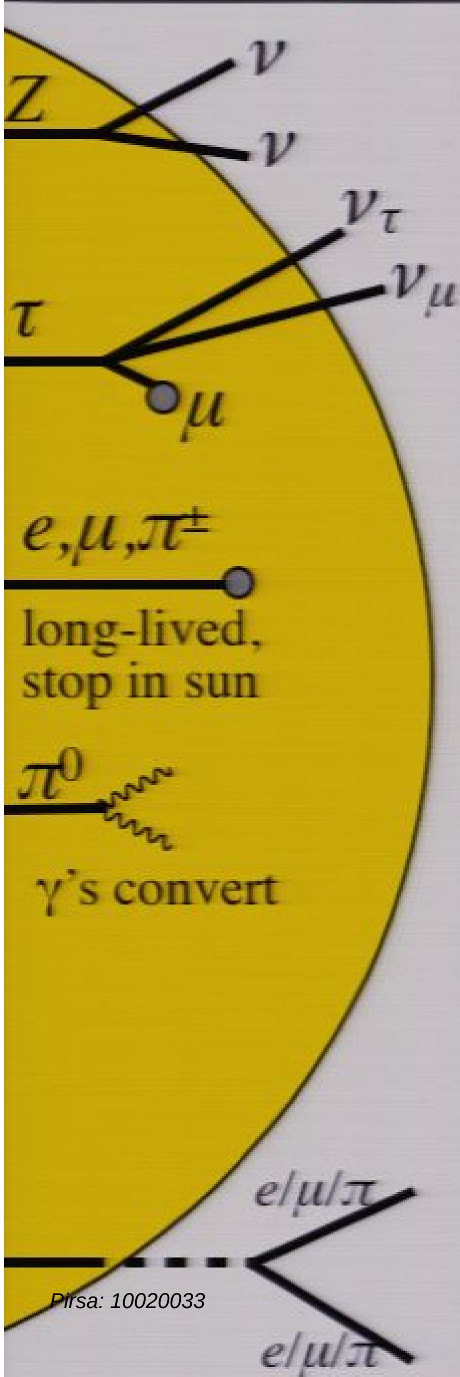
Measured by Fermi up to 5-10 GeV



⇒ **Upper bound on ann. rate**

[Schuster, NT, Yavin; see also .]

Searching for Dark Matter in the Sun



The sun is **also** a giant beam-dump experiment:

Long-lived products of dark matter annihilation escape the sun:

- dark-sector higgs
- exotics with dimension-5 GUT decays

⇒ Solar source of hard e^+e^-?

$$\frac{10^{24}}{\text{second}} \times \frac{1}{4\pi \times 1\text{AU}^2} \sim 3/\text{m}^2/\text{sec}$$

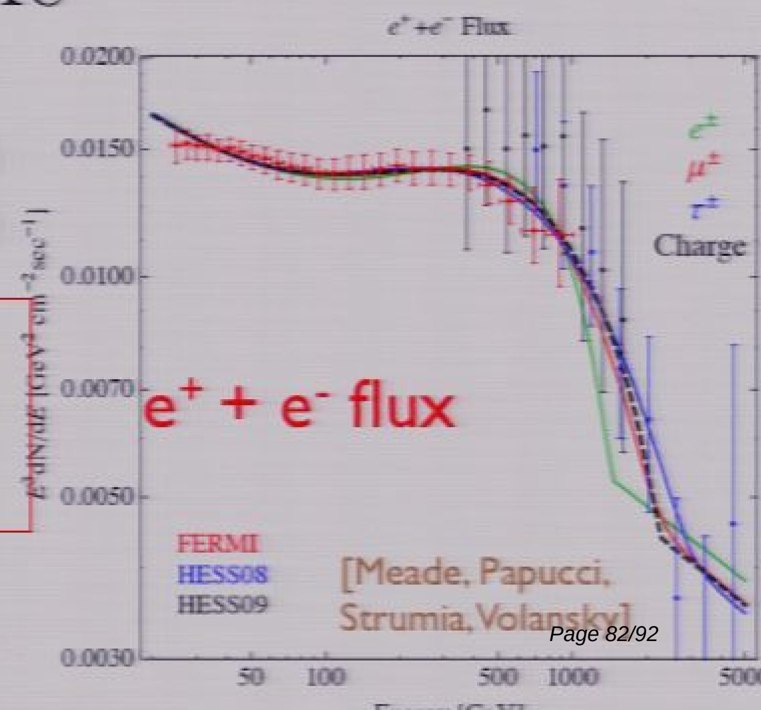
Fermi total flux

$0.08/\text{m}^2/\text{s}$ (E>100 GeV)

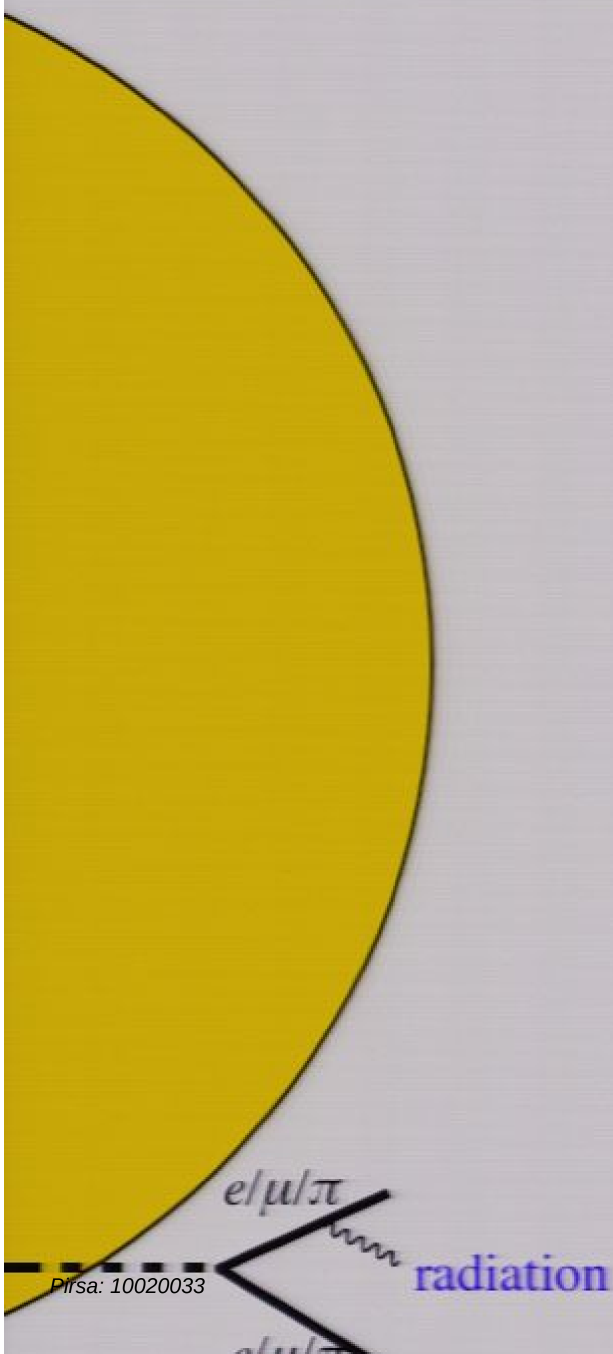
$0.002/\text{m}^2/\text{s}$ (E>500 GeV)

Can annihilation in the Sun be responsible for Fermi excess?

[Schuster, NT, Yavin, Weiner]



Photons/Electrons from DM Annihilation in the Sun?



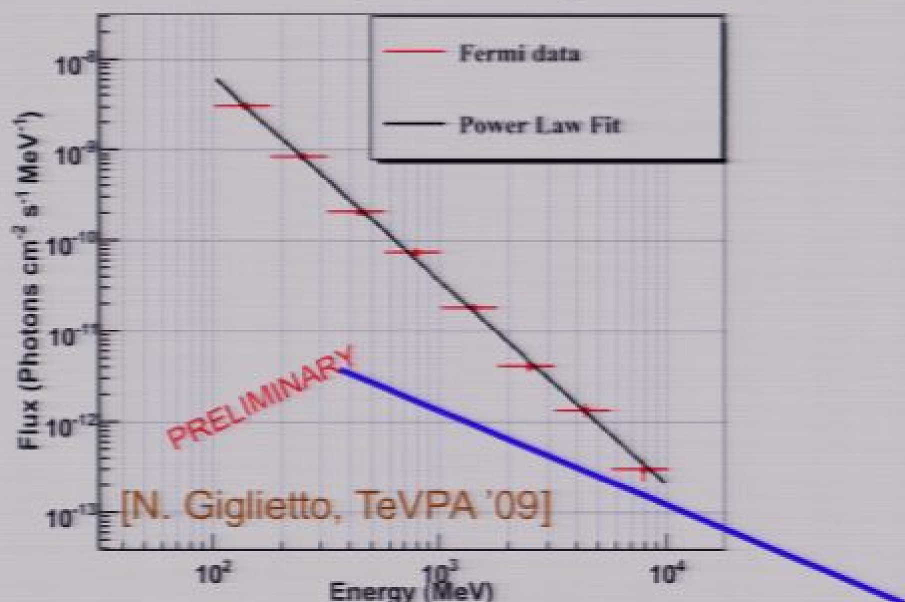
Radiated photons:

– Spectrum ~ $1/E$

– "solar albedo" background ~ $1/E^2$

Inverse Compton scattering of sunlight
Cosmic ray nuclear interactions

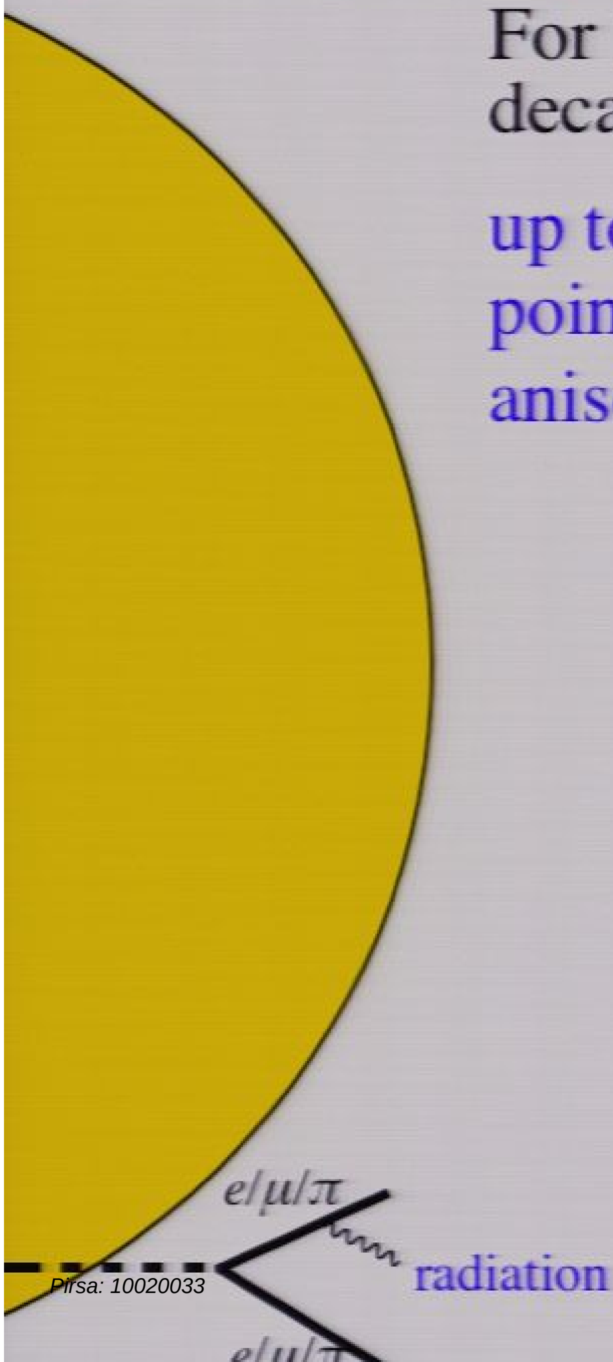
Measured by Fermi up to 5-10 GeV



⇒ Upper bound on ann. rate

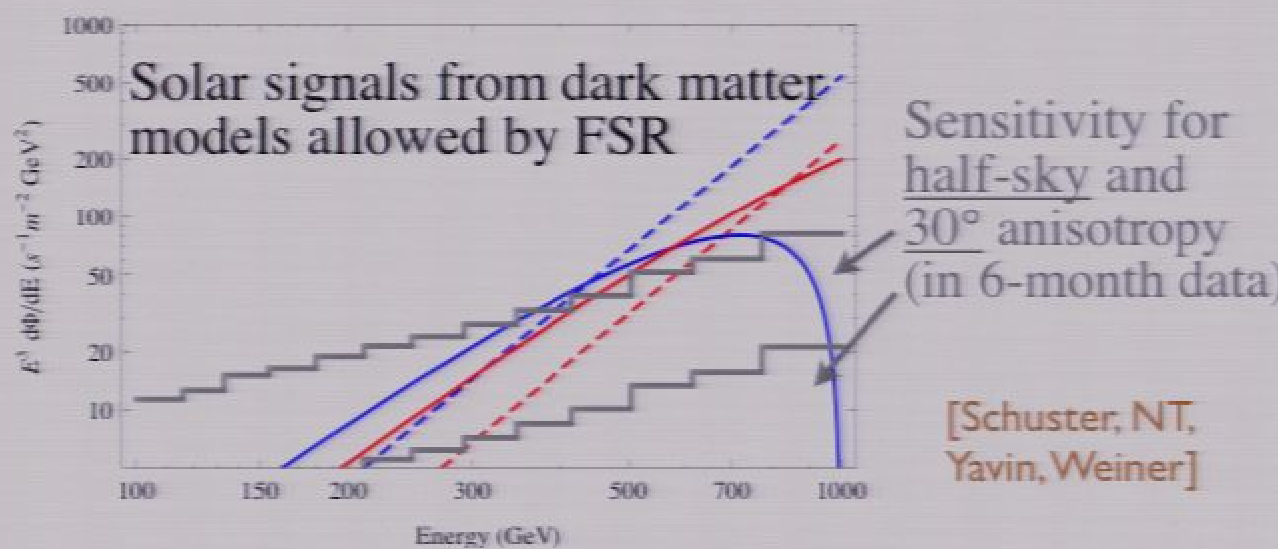
[Schuster, NT, Yavin; see also .]

Signals of Long-Lived Exotics from the Sun



For 1 TeV dark matter, long-lived products decaying to $\mu^+\mu^-$ pairs,

up to 30% of Fermi high-energy e^+e^- flux could point toward sun ⇒ easily observable anisotropy

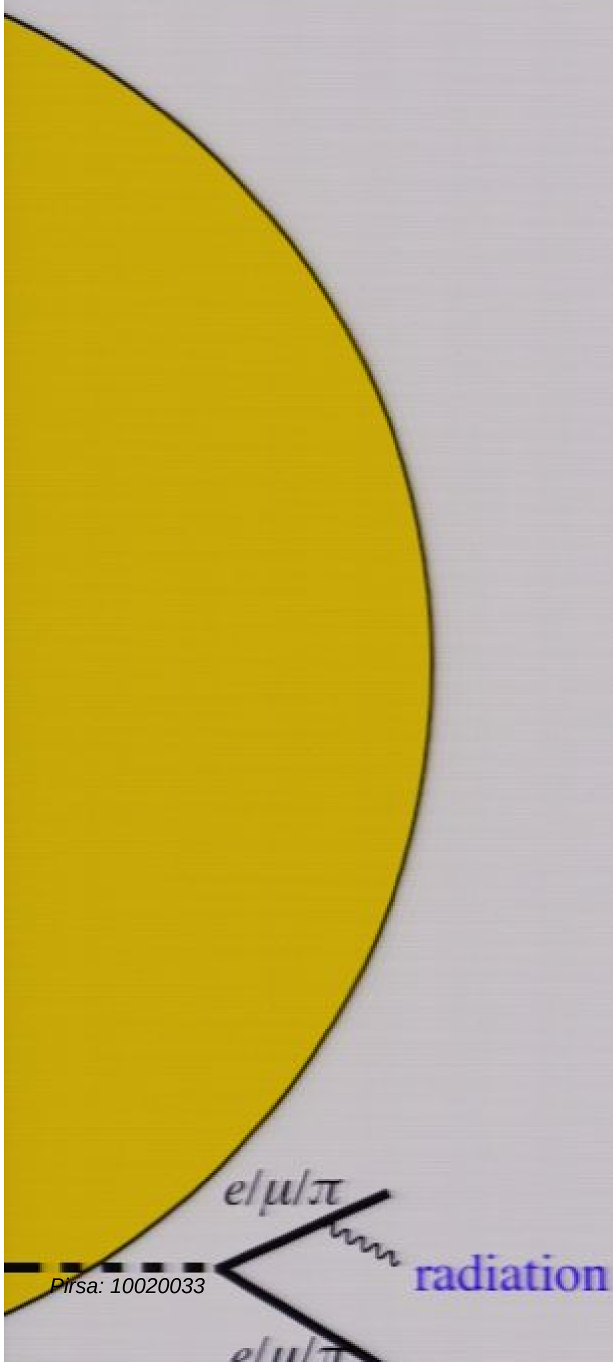


[Schuster, NT, Yavin, Weiner]

Important constraint & possible signal:

Even small branching fraction ~10^{-4} of DM to long-lived exotics is detectable in e and γ!

Photons/Electrons from DM Annihilation in the Sun?

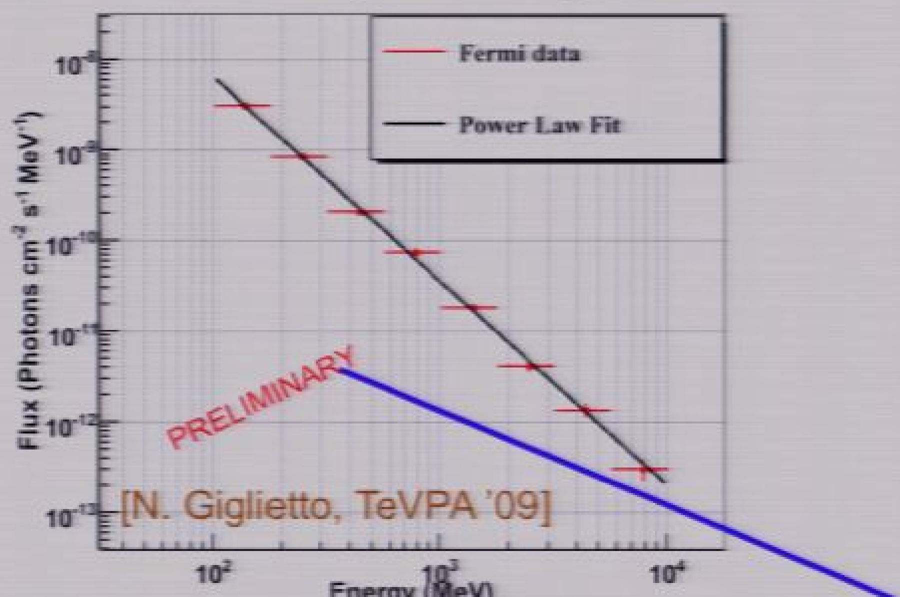


Radiated photons:

- Spectrum ~ $1/E$
- "solar albedo" background ~ $1/E^2$

Inverse Compton scattering of sunlight
Cosmic ray nuclear interactions

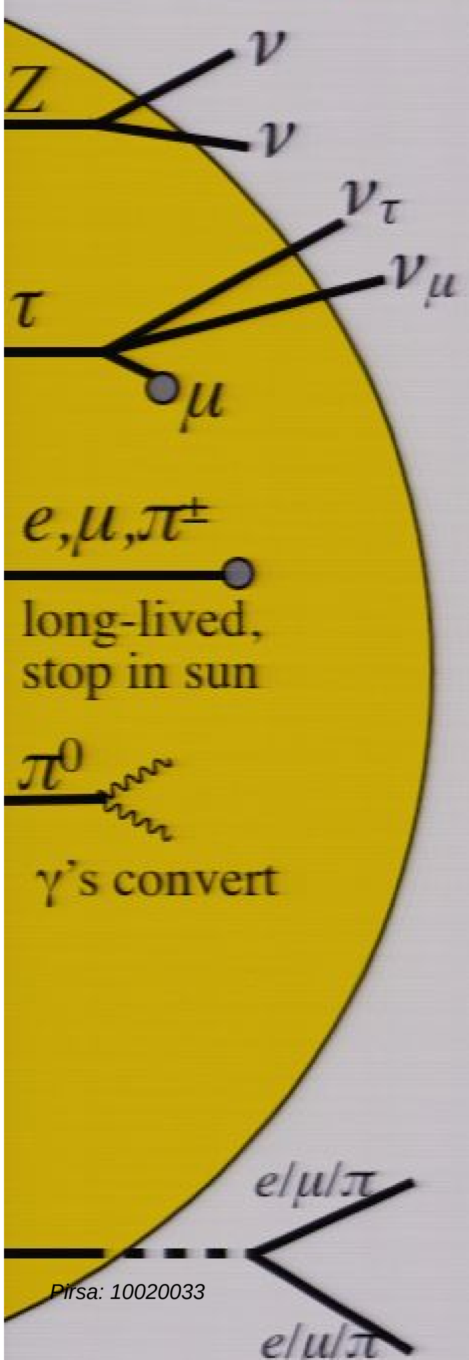
Measured by Fermi up to 5-10 GeV



⇒ Upper bound on ann. rate

[Schuster, NT, Yavin; see also .]

Searching for Dark Matter in the Sun



The sun is **also** a giant beam-dump experiment:

Long-lived products of dark matter annihilation escape the sun:

- dark-sector higgs
- exotics with dimension-5 GUT decays

⇒ Solar source of hard e^+e^-?

$$\frac{10^{24}}{\text{second}} \times \frac{1}{4\pi \times 1\text{AU}^2} \sim 3/\text{m}^2/\text{sec}$$

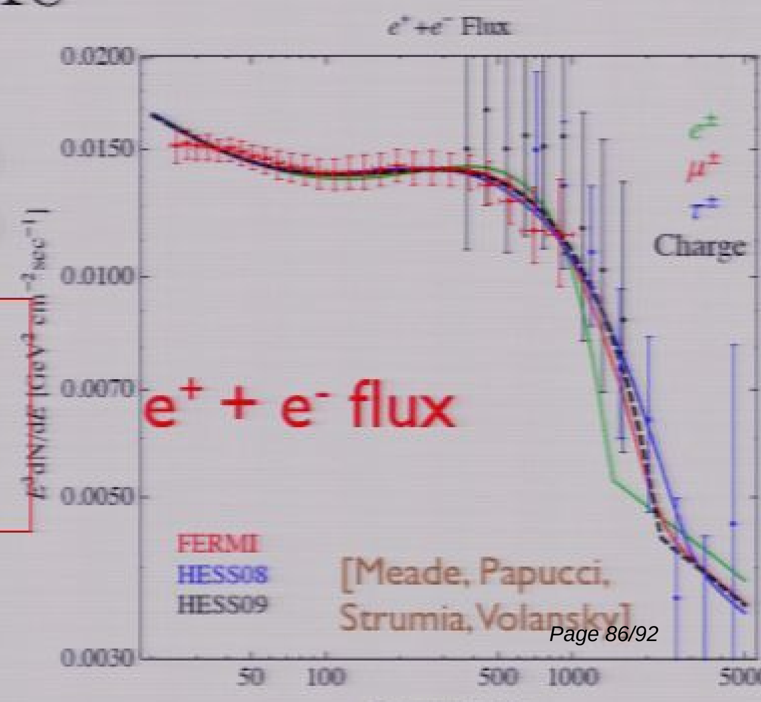
Fermi total flux

$0.08/\text{m}^2/\text{s}$ (E>100 GeV)

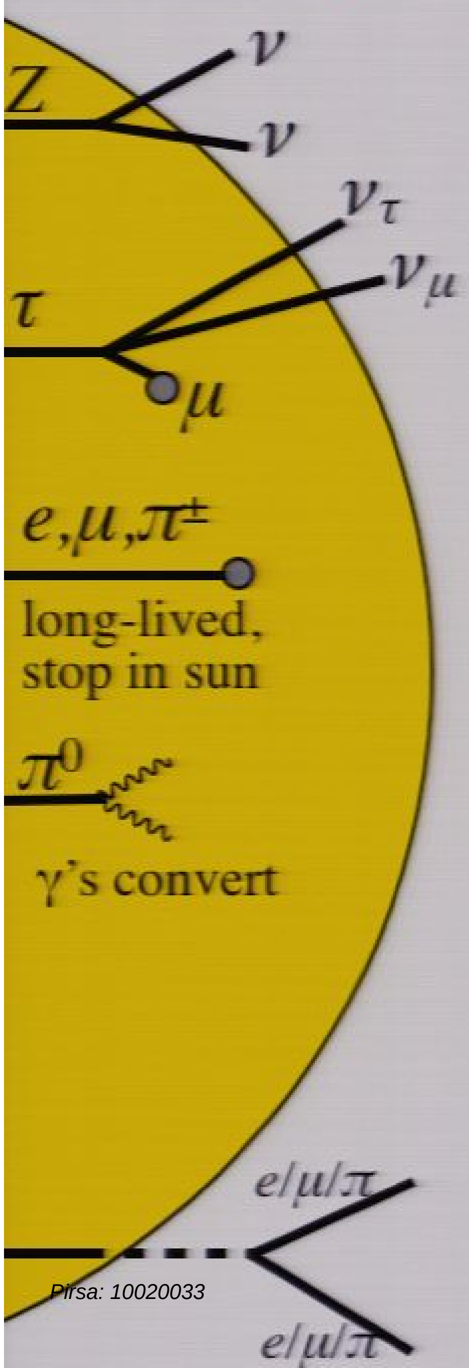
$0.002/\text{m}^2/\text{s}$ (E>500 GeV)

Can annihilation in the Sun be responsible for Fermi excess?

[Schuster, NT, Yavin, Weiner]



Searching for Dark Matter in the Sun



The sun is **also** a giant beam-dump experiment:

Long-lived products of dark matter annihilation escape the sun:

- dark-sector higgs
- exotics with dimension-5 GUT decays

⇒ Solar source of hard e^+e^-?

$$\frac{10^{24}}{\text{second}} \times \frac{1}{4\pi \times 1\text{AU}^2} \sim 3/\text{m}^2/\text{sec}$$

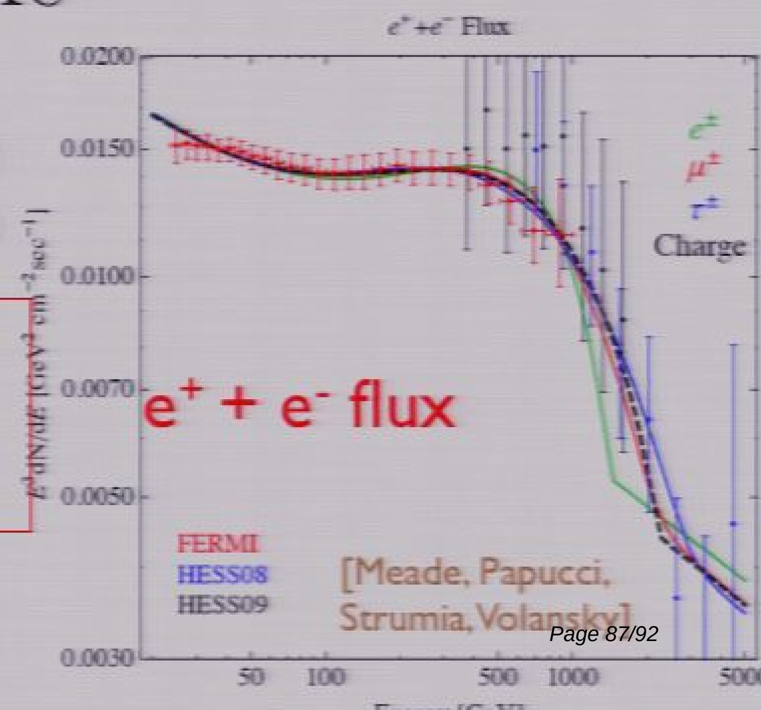
Fermi total flux

$0.08/\text{m}^2/\text{s}$ (E>100 GeV)

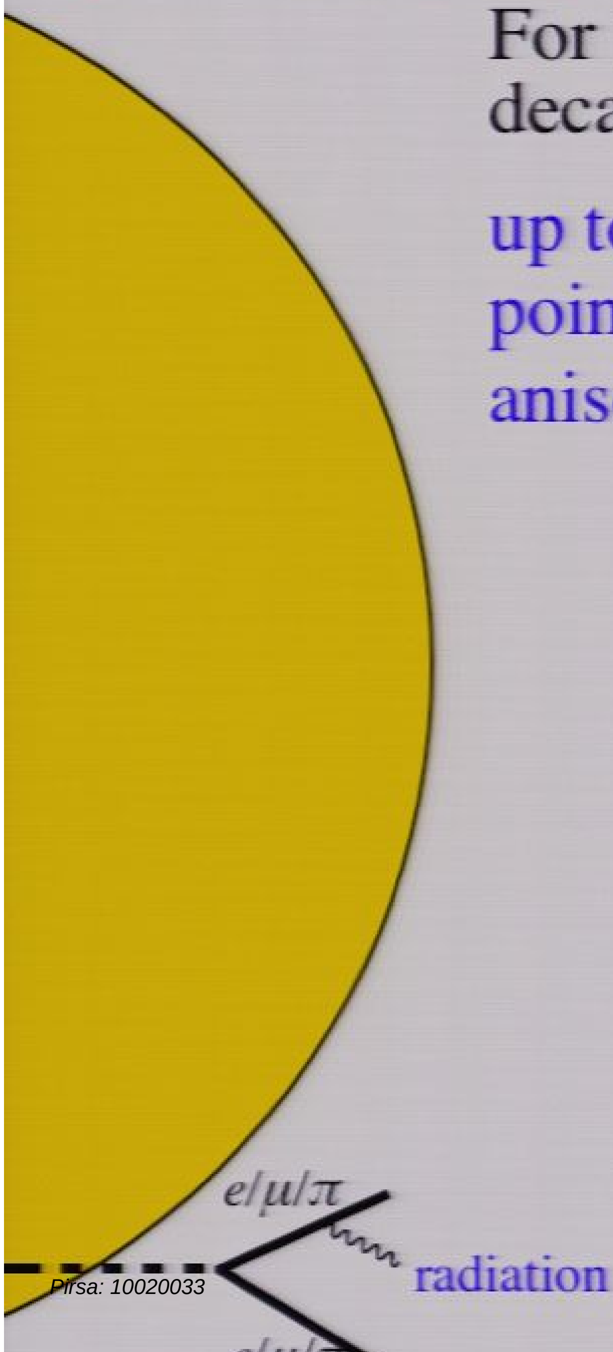
$0.002/\text{m}^2/\text{s}$ (E>500 GeV)

Can annihilation in the Sun be responsible for Fermi excess?

[Schuster, NT, Yavin, Weiner]

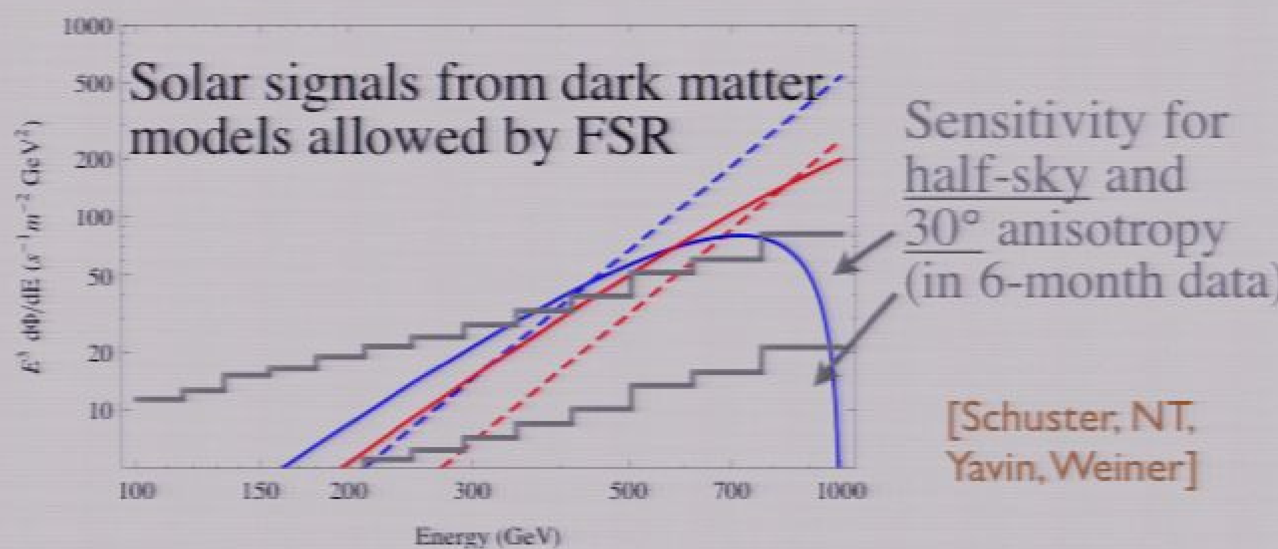


Signals of Long-Lived Exotics from the Sun



For 1 TeV dark matter, long-lived products decaying to $\mu^+\mu^-$ pairs,

up to 30% of Fermi high-energy e^+e^- flux could point toward sun ⇒ easily observable anisotropy

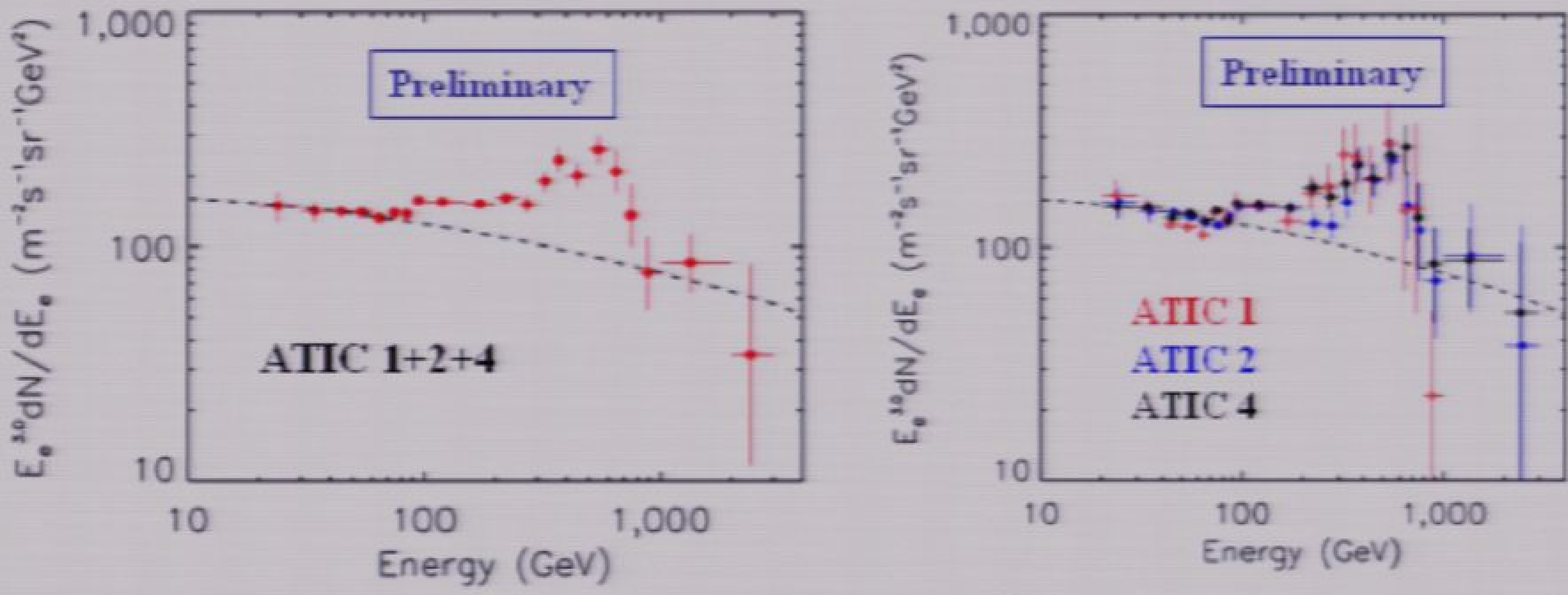


Important constraint & possible signal:

Even small branching fraction ~10^{-4} of DM to long-lived exotics is detectable in e and γ!

Balloon-Based Experiments

All three ATIC flights are consistent



Combined significance: 5.1 σ

Compatible with previous balloon measurement (PPB-BETS)

Excess flux ~5x Fermi excess!

The Bright Future of Dark Matter

Experiments in the last two years have been surprising beyond anyone's expectations — underscores how little we know about dark matter.

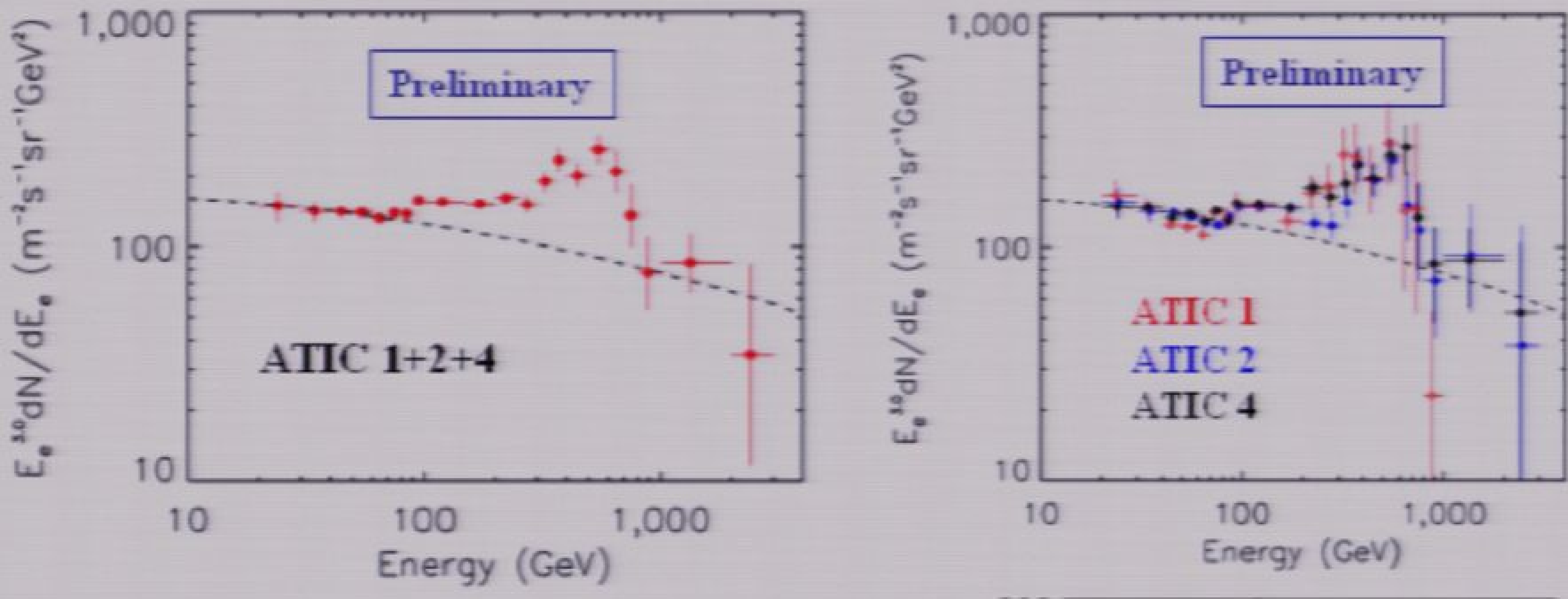
But the data is coming in fast. In the next 1–2 years…

- **Direct detection**: elastic **and** inelastic scattering events at XENON–100?
- **Indirect detection**: precision AMS-II cosmic-ray spectra, new γ-ray sources — large uncertainty in propagation
- **New-Force Searches**: dark-sector discovery in fixed-target, or even spectroscopy of many states at B-factories.

$\Rightarrow$ On the way to a (surprising) Standard Model of dark matter?

Balloon-Based Experiments

All three ATIC flights are consistent



Combined significance: 5.1 σ

Compatible with previous balloon measurement (PPB-BETS)

Excess flux ~5x Fermi excess!

The Bright Future of Dark Matter

Experiments in the last two years have been surprising beyond anyone's expectations — underscores how little we know about dark matter.

But the data is coming in fast. In the next 1–2 years…

- **Direct detection**: elastic **and** inelastic scattering events at XENON–100?
- **Indirect detection**: precision AMS-II cosmic-ray spectra, new γ-ray sources — large uncertainty in propagation
- **New-Force Searches**: dark-sector discovery in fixed-target, or even spectroscopy of many states at B-factories.

$\Rightarrow$ On the way to a (surprising) Standard Model of dark matter?