Dan Hooper - Fermilab/University of Chicago

PATRAS 2012 Workshop

Dark Forces and Light Dark Matter

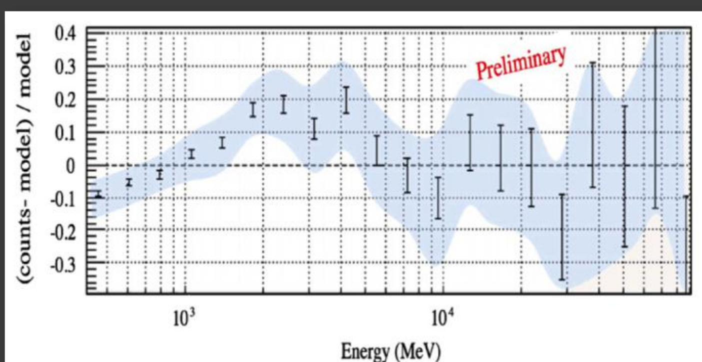
Based On:

Dark Forces and Light Dark Matter,
with Neal Weiner and Wei Xue, arXiv:1206.2929

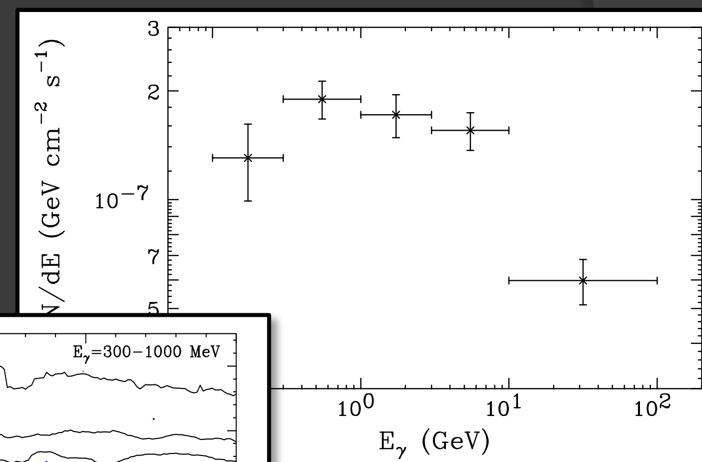
The Empirical Case for 10 GeV Dark Mattter,
Physics of the dark universe, in press, arXiv:1201.1303

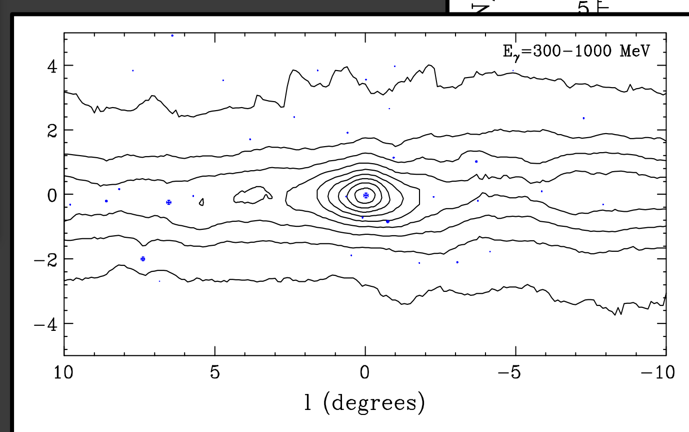
Possible Evidence of Light WIMPs?

- Gamma-rays from the Galactic Center
  - -Excess of spatially extended emission, consistent with cusped halo profile
  - -Bump-like spectrum, peaking at ~GeV energies
  - -Total power consistent with thermal WIMP
  - -Difficult to explain with astrophysics



V. Vitale, for the Fermi Collaboration





Hooper and Linden, PRD, arXiv:1110.0006;
Hooper and Goodenough, PLB, arXiv:1010.2752

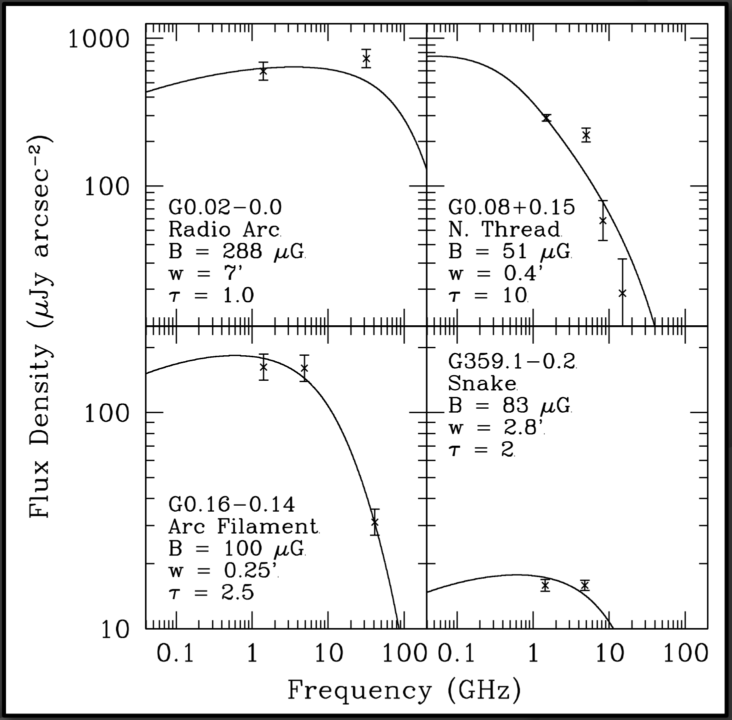
Possible Evidence of Light WIMPs?

- Synchrotron Emission from Milky Way radio filaments

  -Hard spectrum with strong suppression above ~10 GHz, implies the presence of an extremely hard ("monoenergetic") electron spectra, peaking at around ~8 GeV

  -Total power and spectrum consistent with thermal WIMP

  -No known astrophysical explanation for this emission



Linden, Hooper, Yusef-Zadeh, ApJ, arXiv:1106.5493

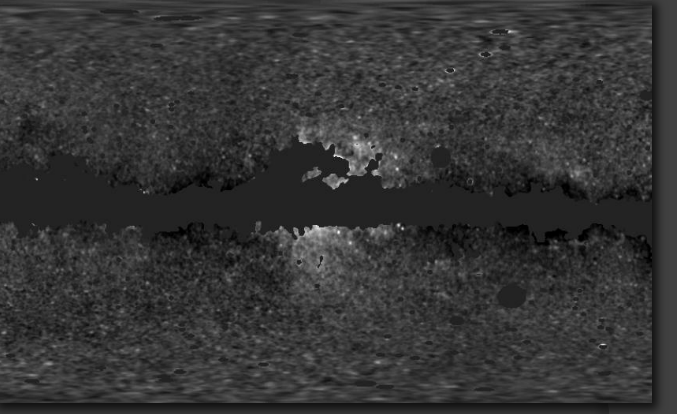
Possible Evidence of Light WIMPs?

- WMAP/Planck/Finkbeiner Haze

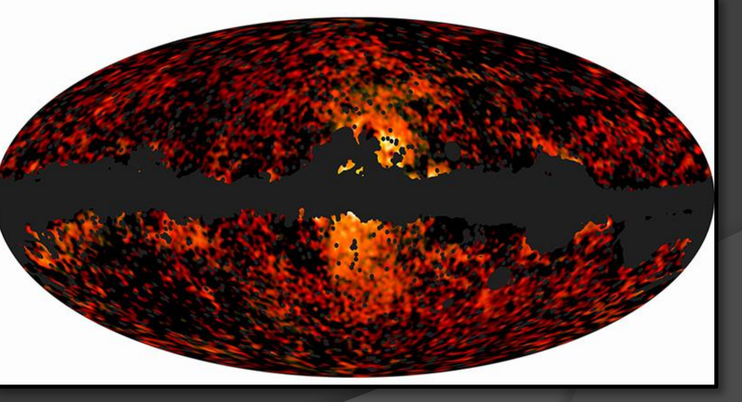
    -In 2004, Doug Finkbeiner discovered an excess of hard synchrotron emission around the Inner Galaxy in WMAP data

    -Recently, the Planck collaboration “unambiguously” confirmed the presence of this synchrotron haze (no paper yet)

    -Origin unknown, but consistent with a thermal WIMP in a cusped distribution



WMAP (22 GHz)



Planck (30 and 44 GHz)

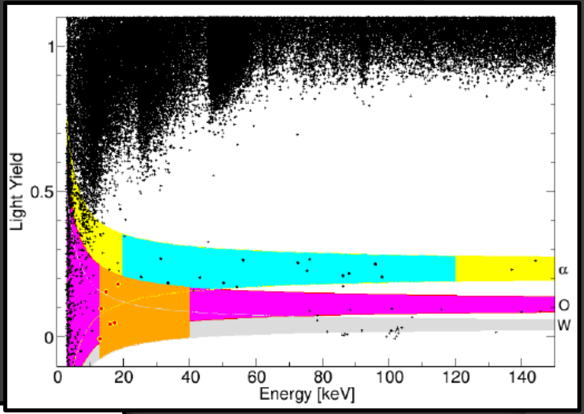
Finkbeiner, astro-ph/0409027;
Hooper, Finkbeiner, Dobler, PRD (2007);
Dobler, Finkbeiner, ApJ (2008)

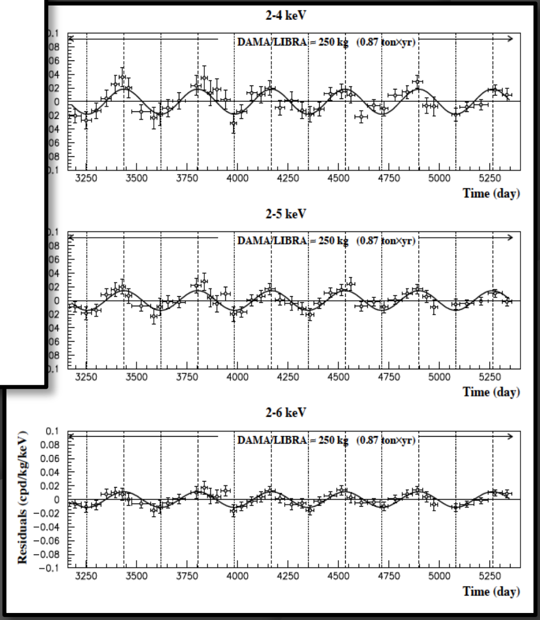
Possible Evidence of Light WIMPs?

- DAMA, CoGeNT, CRESST

-The DAMA/LIBRA collaboration has long reported an annual modulating event rate (at 8.9σ), and have ascribed this behavior to dark matter

-The CoGeNT and CRESST-II experiments have each reported excess events at low energies; consistent with ~10-15 GeV dark matter with a elastic scattering cross section with nucleons of ~10^{-41} cm^2





Kelso, Hooper, Buckley, PRD, arXiv:1110.5338

What kind of WIMP might these experiments be observing?

-Each of these six observations can be accommodated by a dark matter candidate with a mass of about 10 GeV

-If one wants to account for all of these anomalies with a conventional WIMP, however, then that particle must have the following rather specific characteristics:

1) They must annihilate mostly to tau leptons and electrons (to produce the hard gamma-ray spectrum observed from the Galactic Center and the hard synchrotron spectrum from radio filaments, respectively)

2) The total annihilation cross section to these leptonic final states must be $\sim 10^{-26}$ cm^3/s (approximately the value required to produce the observed dark matter abundance in the early universe)

3) The dark matter must be distributed in a cusped distribution, $\rho \sim r^{-1.3}$ (consistent with expectations from hydrodynamical simulations)

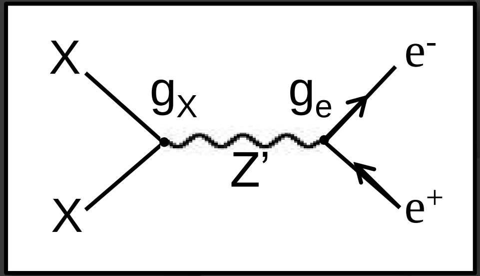
4) The dark matter must possess a spin-independent elastic scattering cross section with nucleons of $\sim 10^{-41}$ cm^2 (assuming equal couplings to protons and neutrons)

Conventional WIMPs?

-While these characteristics can all be found in conventional WIMP models, they often require some rather ad-hoc features.

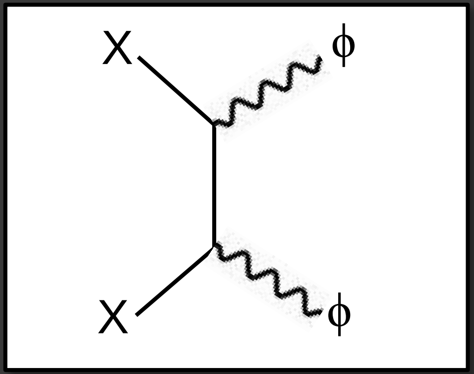
-For example, in order for a 10 GeV WIMP to annihilate with a cross section of ~10^{-26} cm^3/s to e^+e^- without violating constraints from LEP, one is forced to consider a mediator that is either near resonance ($m_{Z'} \sim 2\, m_X$) and/or that couples much more strongly to the dark matter than it does to electrons ($g_X >> g_e$)

-While this is certainly possible, it is far from a generic expectation of commonly studied dark matter models



A Simple Hidden Sector Dark Matter Model

- Introduce a new stable Dirac Fermion, X (our dark matter candidate), which is not charged under the Standard Model
- Introduce a new broken $U(1)_X$ gauge group, under which the dark matter is charged (but the Standard Model is not)
- If the vector associated with the $U(1)_X$, ϕ, is lighter than the dark matter, then the dark matter will annihilate dominantly via:



$$\sigma v_{XX\to\phi\phi} \simeq \frac{\pi\alpha_X^2}{m_X^2} \approx 3\times10^{-26}\,\mathrm{cm}^3/\mathrm{s}\left(\frac{g_X}{0.06}\right)^4\left(\frac{10\,\mathrm{GeV}}{m_X}\right)^2$$

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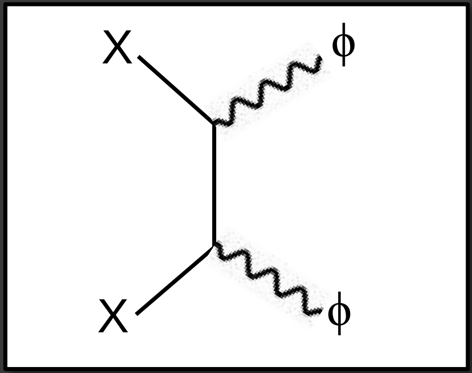

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-A very reasonable value of g_X~0.06 thermally generates the observed dark matter abundance

-Throughout this talk, we fix g_X to this value

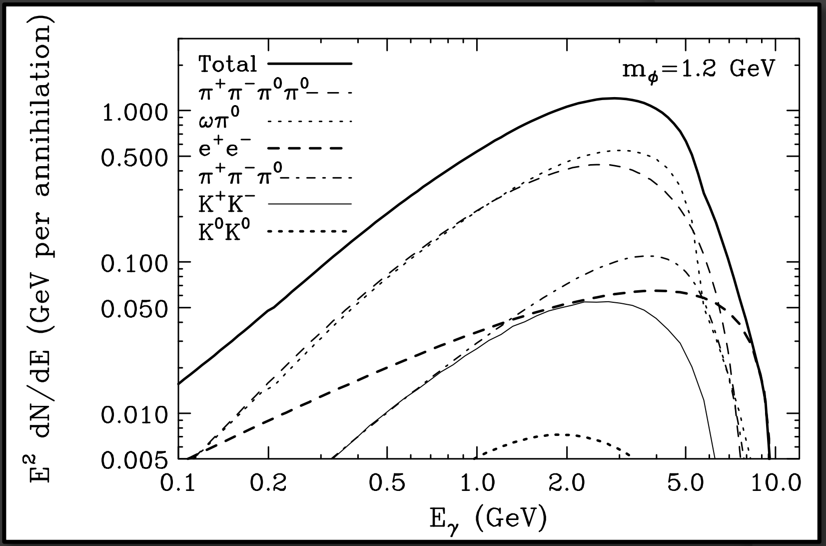
Kinetic Mixing and ϕ Decays

- Neither the dark matter, X, nor the force carrier, ϕ, possess any tree-level couplings to the Standard Model (they are part of a "hidden sector")
- The ϕ interacts with the Standard Model through (a small degree of) kinetic mixing with electromagnetism; inducing effective couplings proportional to electric charge
- The dominant decay channels of the ϕ depend on its mass: for light masses (less than a few hundred MeV) decays to electrons/muons dominate, whereas heavier ϕ's also decay to mesons (or to quarks, for masses above a few GeV)

$$\mathcal{L} = \frac{1}{2}\epsilon F'_{\mu\nu} F^{\mu\nu}$$

The Gamma Ray Spectrum

- As an example, consider m_ϕ=1.2 GeV
- In this case, the ϕ decays produce gamma rays mostly through the decays of neutral mesons
- This leads to a very hard spectrum, similar to that predicted from dark matter annihilations to tau leptons



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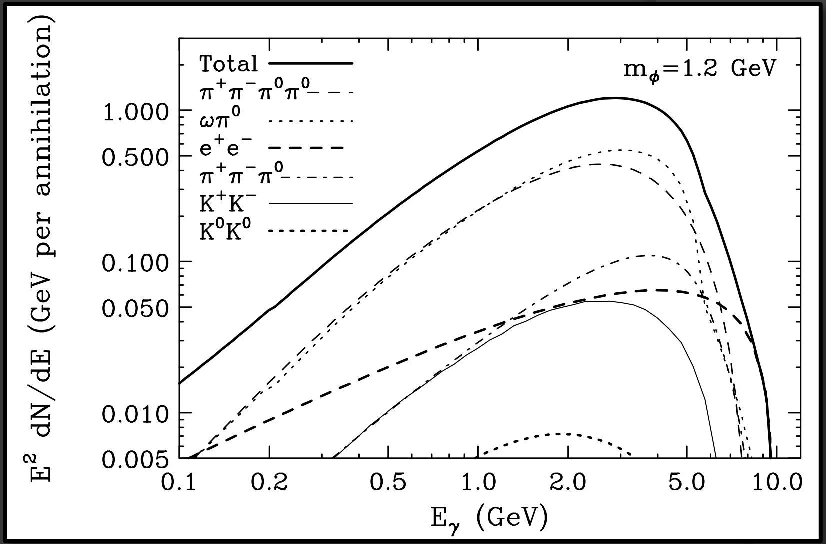
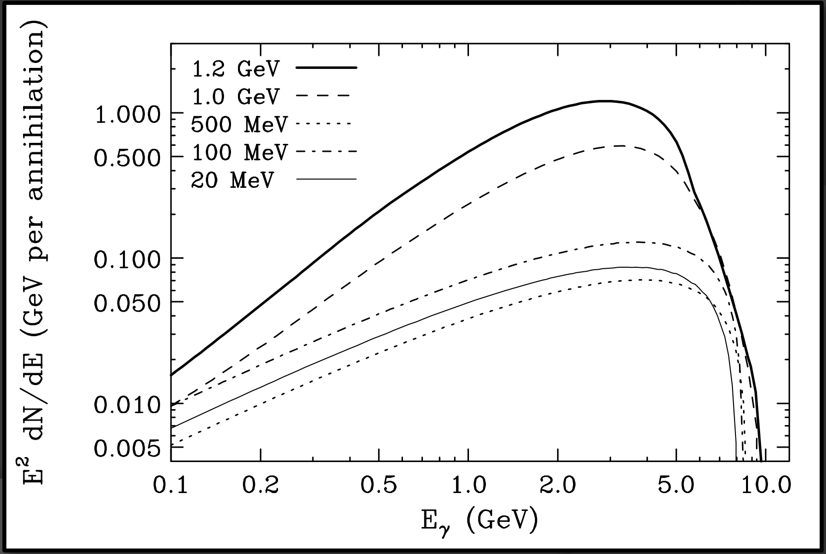
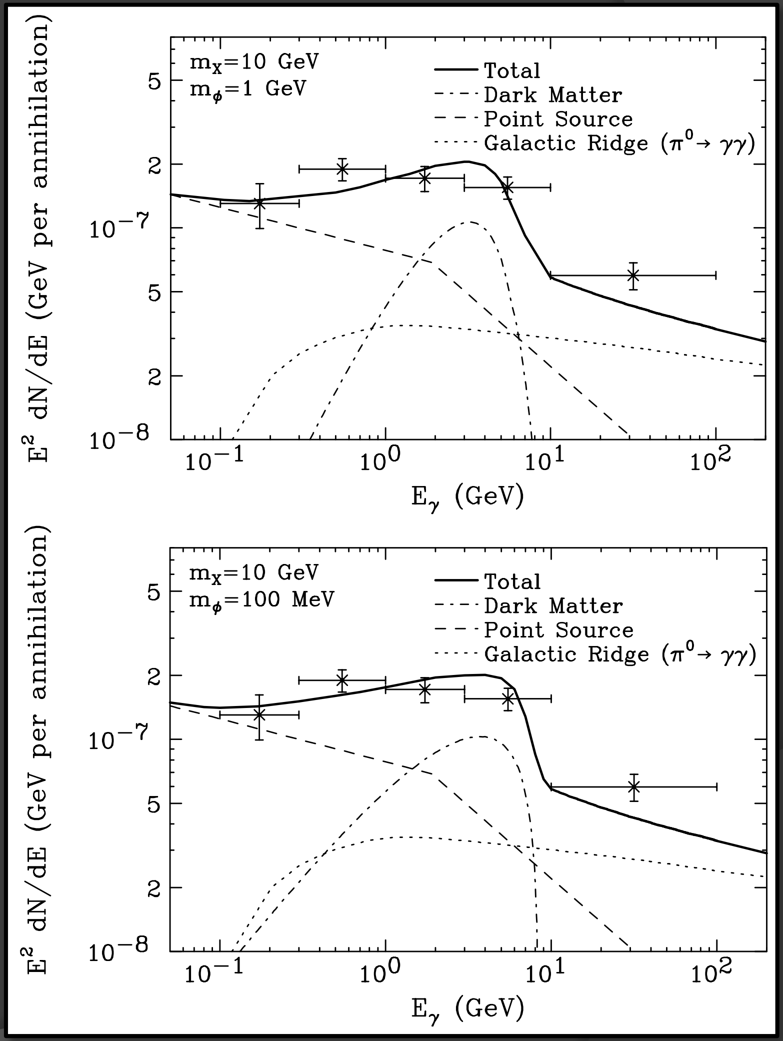
- Although the shape of the gamma-ray spectrum varies with m_ϕ, a hard spectrum peaking at $\sim m_X/3$ is a generic prediction of these models
- A significant fraction of decays also proceed to e^+e^-, naturally accommodating the observed radio filaments and synchrotron haze





The Gamma-Ray Spectrum

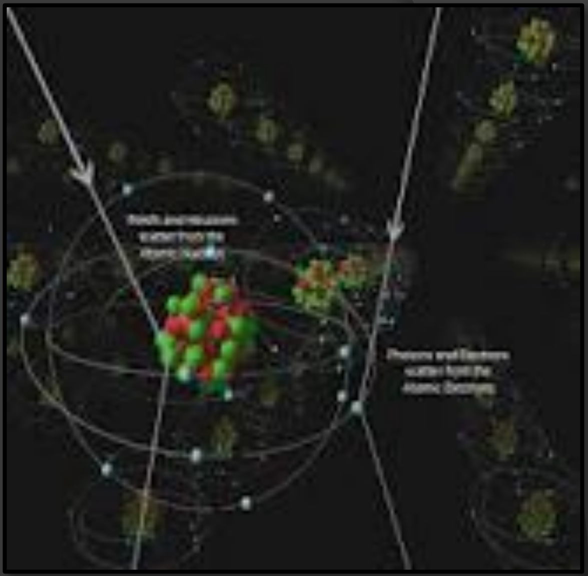
- This is in good agreement with the hard, few GeV bump observed from the Galactic Center by Fermi
  (the gamma-ray spectrum predicted in this class of models strongly resembles that from conventional WIMPs annihilating to taus)
- Observed spectrum can be accommodated for a wide range of masses, m_ϕ~10 MeV-few GeV
  (generic prediction, no parameter tuning)



Elastic Scattering

- In this model, dark matter scatters elastically with protons through the exchange of a ϕ (again, through kinetic mixing with the photon)
- The predicted elastic scattering cross section with *protons* is given by:

$$\sigma_{Xp} = \frac{g_2^2 \sin^2\theta_W g_X^2 \epsilon^2 m_X^2 m_p^2}{\pi m_\phi^4 (m_X + m_p)^2}$$
$$\approx 1.6 \times 10^{-40}\,\mathrm{cm}^2 \left(\frac{\epsilon}{7\times 10^{-5}}\right)^2 \left(\frac{1\,\mathrm{GeV}}{m_\phi}\right)^4$$



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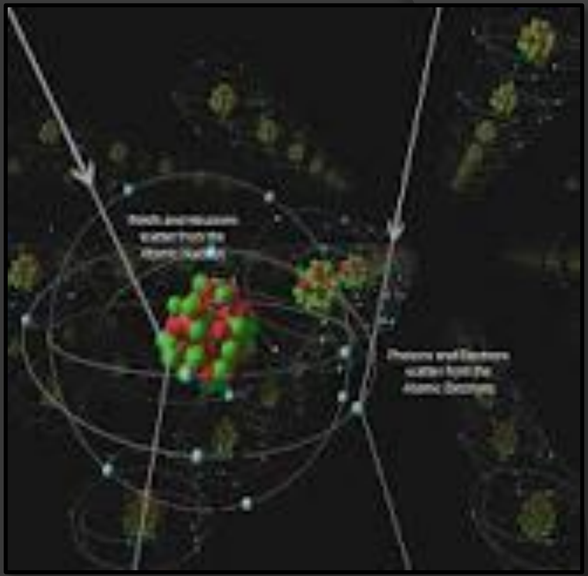

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Approximate cross section needed to explain DAMA/CoGeNT/CRESST

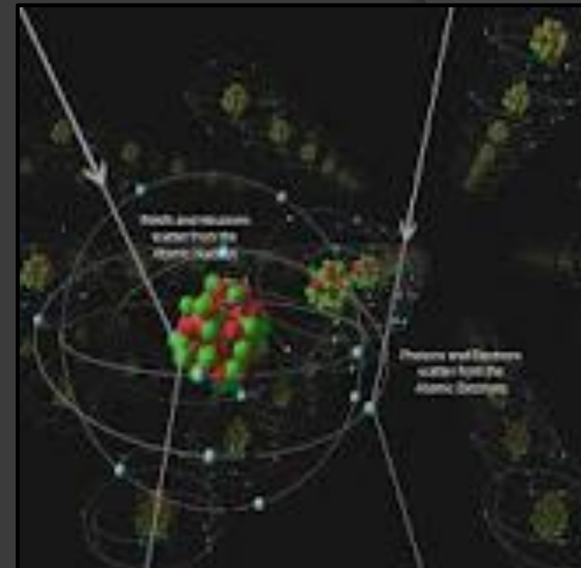
- Direct detection anomalies require $\varepsilon \sim 7 \times 10^{-5} (m_\phi/\mathrm{GeV})^2$
- This is number small? Big? Plausible? Outlandish?

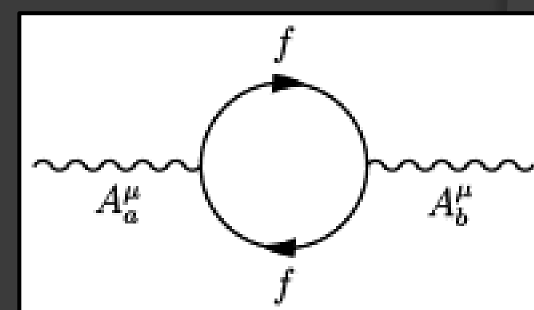
Elastic Scattering

- From an effective field theory standpoint any value of ε is technically natural
- If the Standard Model is embedded in a GUT, however, ε can only be generated through loops of particles carrying both hypercharge and X-gauge charge, leading to:

$$\epsilon \sim \frac{g_X g_Y \cos\theta_W}{16\pi^2} \log\left(\frac{M'}{M}\right) \sim 1.2 \times 10^{-4} \log\left(\frac{M'}{M}\right)$$

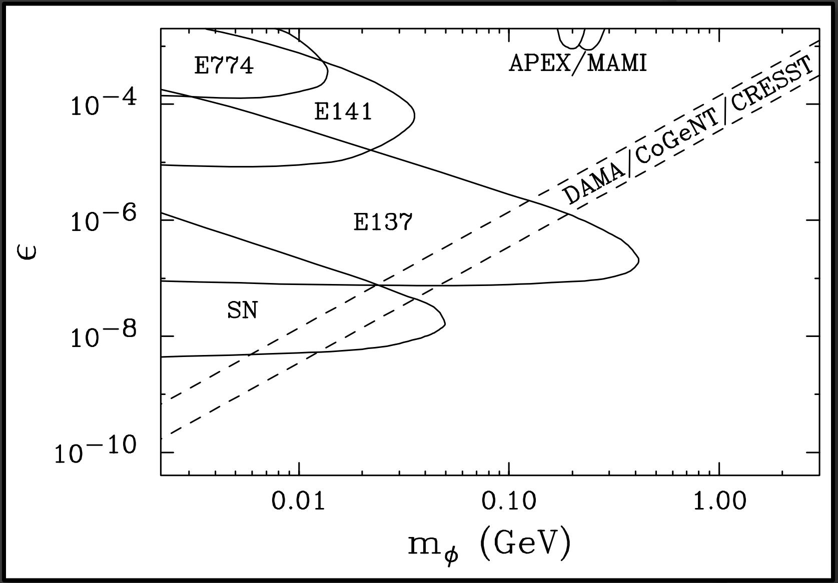
- For $m_\phi \sim$ GeV, this estimate is in good agreement with the value required by direct detection anomalies, $\epsilon \sim 7 \times 10^{-5} (m_\phi/\text{GeV})^2$





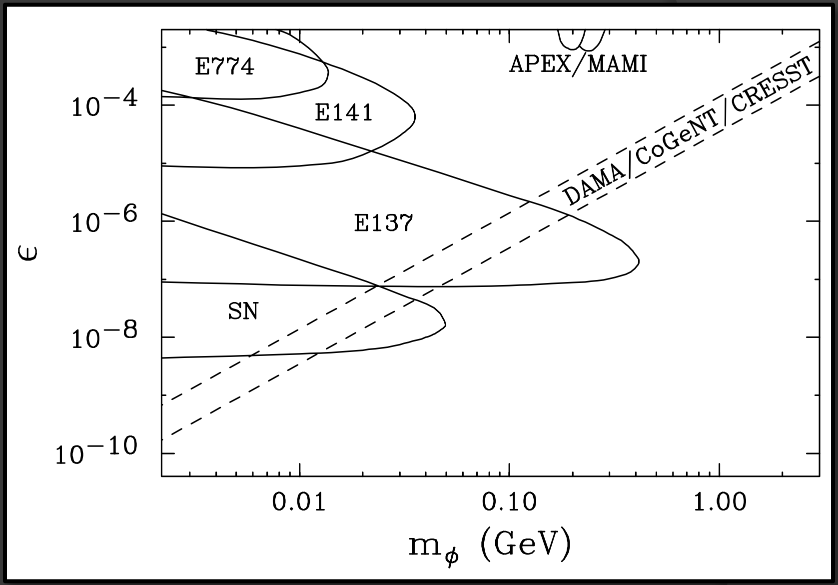
Constraints

- Laboratory and astrophysical constraints on dark photons leave wide open a range of ϕ masses between ~200 MeV and a few GeV



Summary of Model Parameters

- In our simple $U(1)_X$ model, there are only four free parameters: m_X, m_ϕ, g_X and ε



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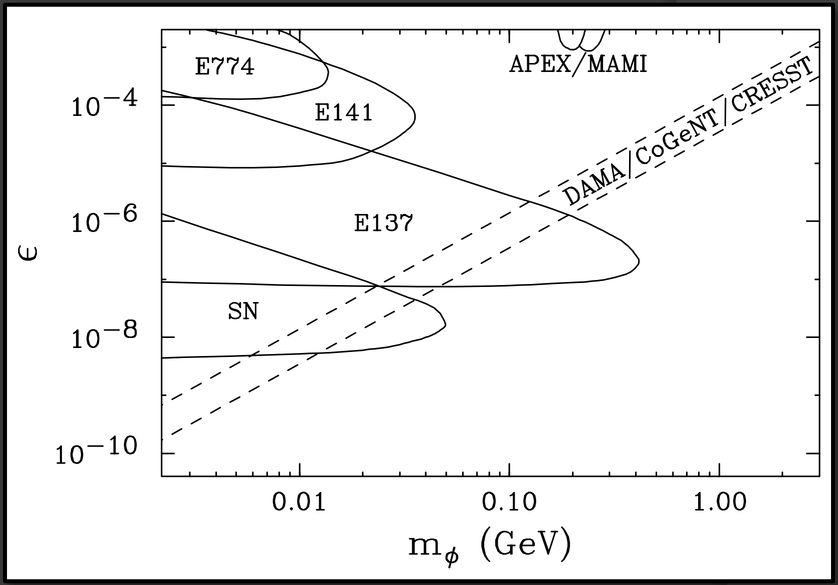

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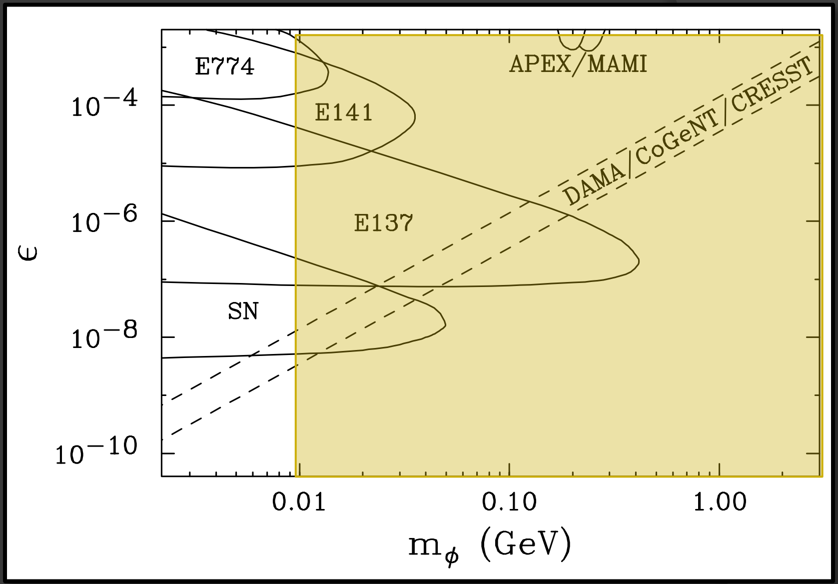

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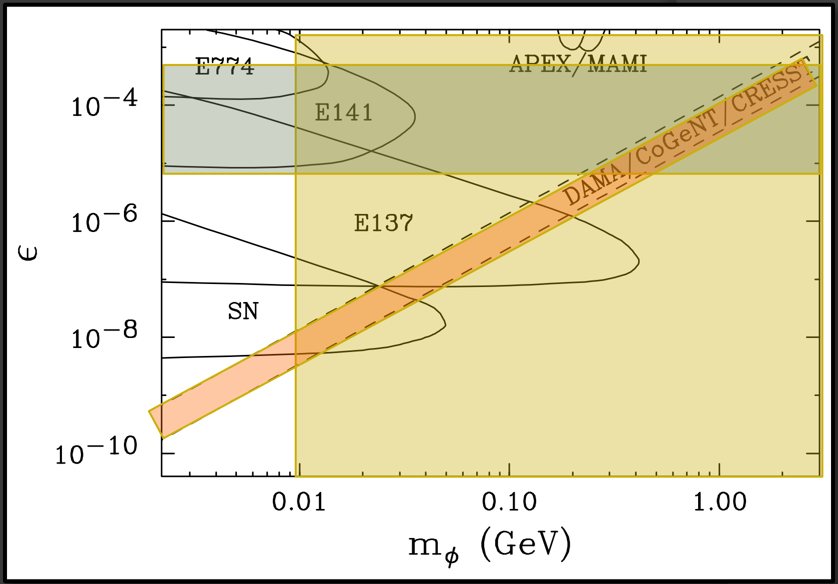
- To also account for direct detection anomalies, we require kinetic mixing at the level of $\varepsilon \sim 10^{-3}$ to 10^{-6} (for m_ϕ~ few GeV to 100 MeV) – in good agreement with generic loop estimate



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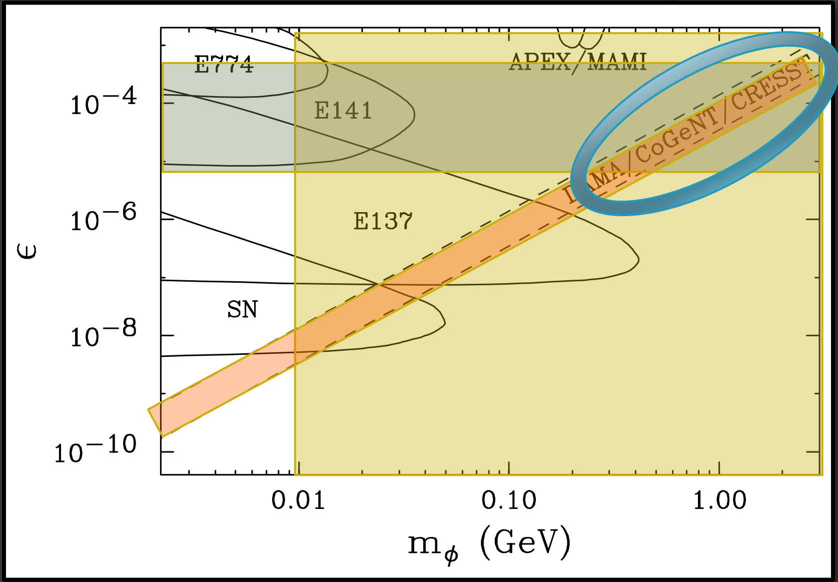

Signals similar to the observed indirect and direct detection anomalies are generically expected in models with a 10 GeV dark matter candidate coupled to a new light gauge boson

Conclusions

- A number of indirect and direct detection anomalies have been reported, and interpreted as possible signals of a ~10 GeV dark matter species
- Conventional WIMP models (those which couple directly to the Standard Model) can explain these observations, but such models tend to have features which appear ad-hoc or tuned
- With this motivation in mind, we have considered a simple dark force model: an additional broken $U(1)_X$ with a corresponding light force carrier, ϕ
- For a broad and well motivated range of parameter space, this model leads to:

1) The observed thermal relic abundance (for g_X~0.06)

2) The observed gamma ray and synchrotron signals (for m_ϕ~0.01-3 GeV)

3) An elastic scattering rate consistent with anomalies reported by DAMA, CoGeNT, CRESST (for $\varepsilon \sim 10^{-4}$, m_ϕ~GeV)

A Last Remark…

- As the LHC excludes more and more of the parameter space of various popular weak-scale extensions of the Standard Model (squarks up to 1400 GeV!), alternatives which can more easily elude collider searches become more attractive

- Simple hidden sector/dark force models, with no tree-level couplings to the Standard Model, can be easily invisible to the experiments of the LHC