Dark Forces and New Physics at the Intensity Frontier

Maxim Pospelov

University of Victoria, Victoria/Perimeter Institute, Waterloo

38 years rule = new forces of nature are discovered every 38 years for the last 150 yrs

1. 1860s – first papers of Maxwell on EM. Light is EM excitation. E & M unification.
2. 1897 – Becquerel discovers radioactivity – first evidence of weak charged currents (in retrospect).
3. 1935 – Chadwick gets NP for his discovery of neutron with subsequent checks that there exists strong n-p interaction. Strong force is established.
4. 1973 – Gargamelle experiment sees the evidence for weak neutral currents in nu-N scattering
5. 2011/2012 Discovery of the Higgs, i.e. new Yukawa force.
6. *Prediction: Discovery of a new dark force – 2050?*

(+/- 2 years or so).

Outline of the talk

1. Energy and Intensity Frontiers. Portals to SM. Implications of the LHC results.
2. "Anomalies" and various rationales for dark forces at low energy. Secluded U(1) (= dark photon) model. Possible connection to dark matter. Main features and signatures.
3. *Selected new results/ideas for secluded sectors:*

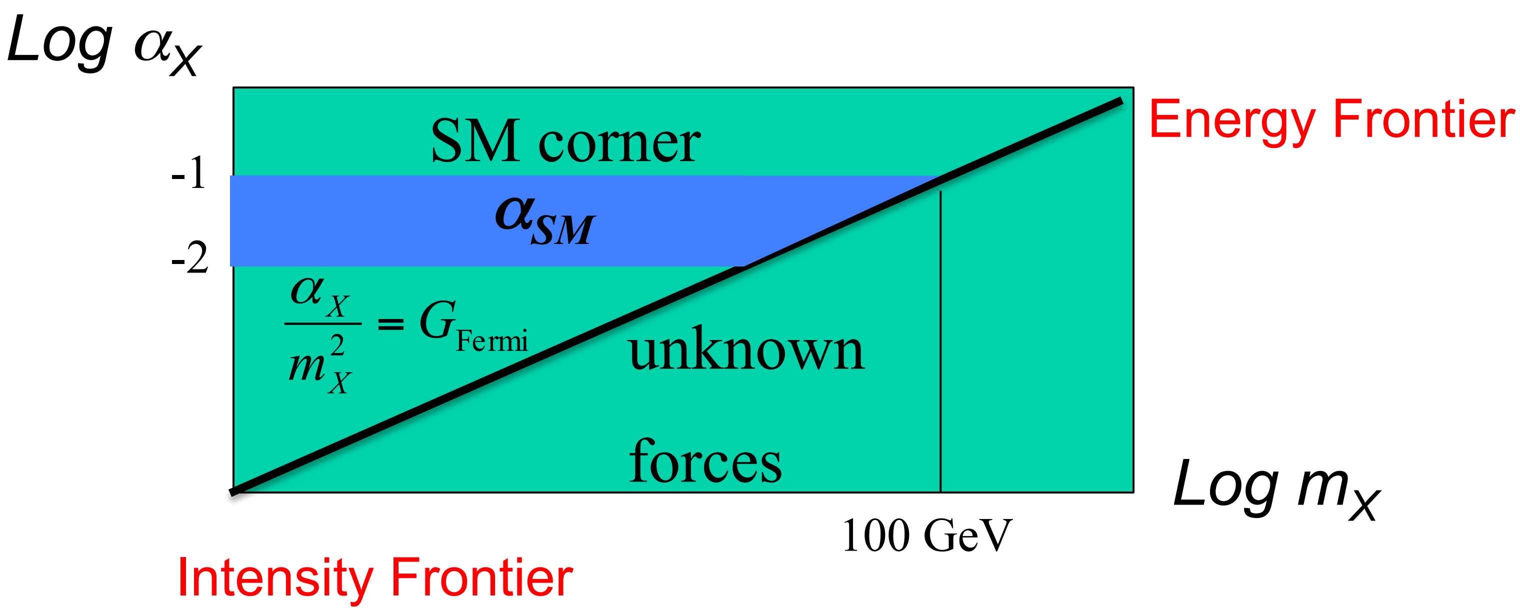
    3a. Fixed target searches of dark photons and light (MeV scale) dark matter

    3c. Very very dark photons. Implication for CMB/BBN + constraints from direct detection.

    3d. Dark forces and ~~world peace~~ B-modes.

4. Conclusions.

Intensity and Energy Frontiers



$$V(r) = \frac{\alpha_X}{r}\exp(-r/\lambda_X) = \frac{\alpha_X}{r}\exp(-rm_X) \longrightarrow \text{Amplitude} \approx \frac{\alpha_X}{q^2 + m_X^2}$$

LHC can realistically pick up New Physics with $\alpha_X \sim \alpha_{SM}$, and $m_X \sim$ 1TeV, while having no success with $\alpha_X < 10^{-6}$, and $m_X \sim$ GeV.

Neutral doors ["portals"] to the SM

Let us *use* these doors, and attach the Dark Matter to the SM

$H^{+}H\,(\lambda\, S^2 + A\, S)$ Higgs-singlet scalar interactions

$B_{\mu\nu} V_{\mu\nu}$ "Kinetic mixing" with additional U(1)' group

(becomes a specific example of $J_\mu^i A_\mu$ extension)

$LH\,N$ neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal…

Dim>4

$J_\mu^A\ \partial_\mu a/f$ axionic portal

……….

$$\mathcal{L}_{\rm mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}^{(k)}_{\rm med}\mathcal{O}^{(l)}_{\rm SM}}{\Lambda^n},$$

Simplest example of a dark force

(Holdom 1986; earlier paper by Okun')

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi),$$

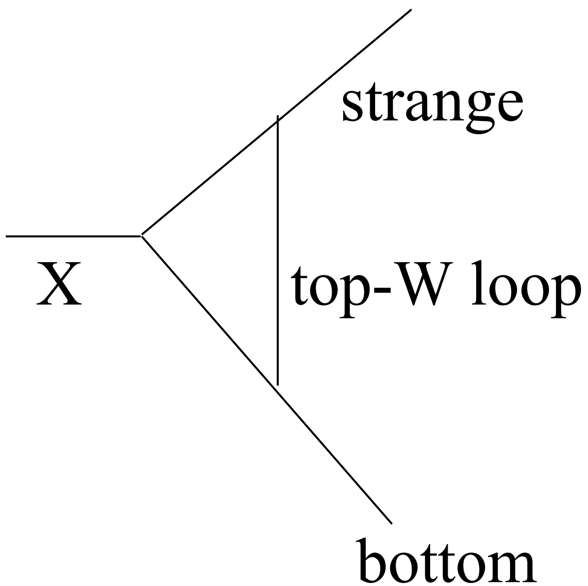
This Lagrangian describes an extra U(1)' group (**dark force, hidden photon, secluded gauge boson, shadow boson etc, also known as U-boson, V-boson, A-prime, gamma-prime etc**), attached to the SM via a vector portal (kinetic mixing). Mixing angle κ (also known as ε, η) controls the coupling to the SM. New gauge bosons can be light if the mixing angle is small.

Low-energy content: Additional massive photon-like vector V, and a new light Higgs h', both with small couplings.

Well over 100 theory papers have been written with the use of this model in some form in the last four years.

Why EM or baryonic currents are "safe" from flavor constraints

Conserved vector currents are uniquely positioned to avoid very strong flavor constraints. Axial vector portals, Higgs portals are potentially liable to very strong flavor constraints. Consider generic FCNC penguin-type loop correction.

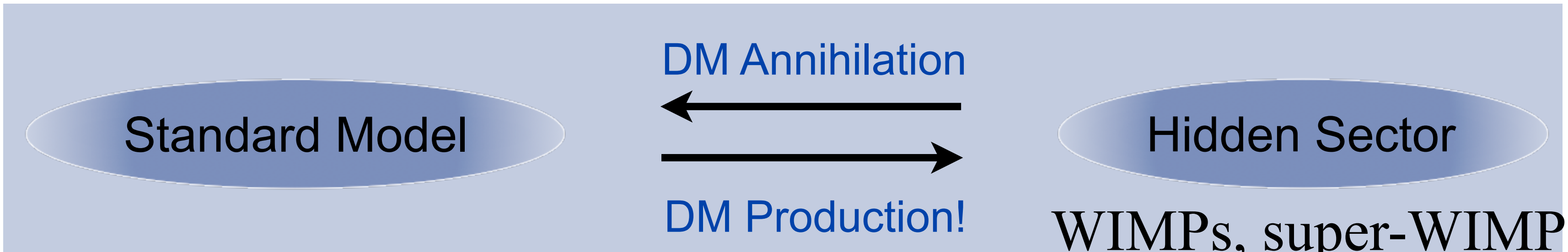


For a conserved vector current, $G_F\, q^2$

For axial vector current, $G_F\, m_t^2$

There is extremely strong sensitivity to new scalars, pseudoscalars axial-vectors in rare K and B decays.

Possible connection to WIMP-y dark matter



WIMPs, super-WIMPs

Mediators (SM Z, h etc or dark force)

Heavy WIMP/heavy mediators: - "mainstream" literature

Light WIMPs/light mediators: Boehm et al; Fayet; MP, Ritz, Voloshin; Hooper, Zurek; others

Heavy WIMPs/light mediators: Finkbeiner, Weiner; Pospelov, Ritz, Voloshin (secluded DM); Arkani-Hamed et al., many others

Light WIMPs/heavy mediators: does not work. (Except for super-WIMPs; or non-standard thermal history)

“Non-decoupling” of secluded U(1)
Theoretical expectations for masses and mixing

Suppose that the SM particles are not charged under new $U_S(1)$, and communicate with it only via extremely heavy particles of mass scale Λ (however heavy!, e.g. 100000 TeV) charged under the SM $U_Y(1)$ and $U_S(1)$ (B. Holdom, 1986)

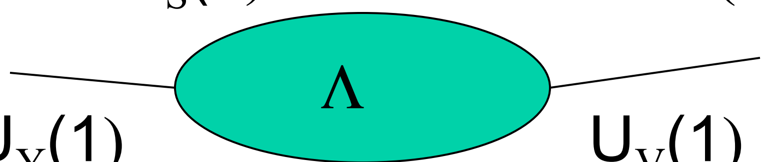


Diagram $U_Y(1)$ —— $U_V(1)$ does not decouple!

A mixing term is induced, $\kappa F^Y_{\mu\nu} F^S_{\mu\nu}$,

With κ having only the log dependence on mass scale Λ

$\kappa \sim (\alpha\alpha')^{1/2} (3\pi)^{-1} \log(\Lambda_{UV}/\Lambda) \sim 10^{-3}$

$M_V \sim e'\kappa M_{EW}$ (M_Z or TeV) ~ MeV – GeV

This is very “realistic” in terms of experimental sensitivity range of parameters.

Some specific motivations for new states/ new forces below GeV

1. Theoretical motivation to look for an extra U(1) gauge group.
2. Recent intriguing results in astrophysics. 511 keV line, PAMELA positron rise.
3. A decade old discrepancy of the muon g-2.
4. New discrepancy of the muonic hydrogen Lamb shift.
5. Other motivations.

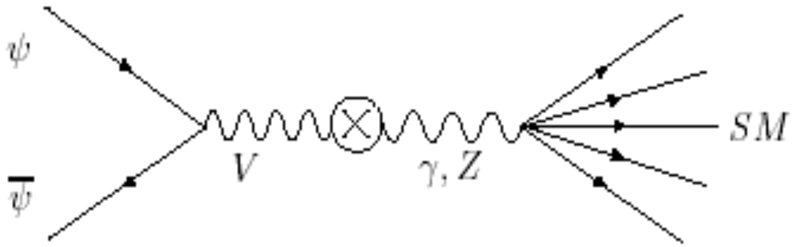
….

Secluded WIMP idea – heavy WIMPs, light mediators

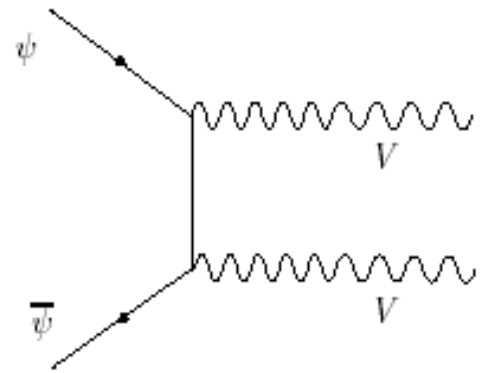
$$\mathcal{L}_{\rm WIMP+mediator} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}B_{\mu\nu} - |D_\mu\phi|^2 - U(\phi\phi^*) + \bar{\psi}(iD_\mu\gamma_\mu - m_\psi)\psi.$$

ψ – weak scale Dark Matter; V –mediator particle.

$m_{mediator} > m_{WIMP}$



$m_{mediator} < m_{WIMP}$

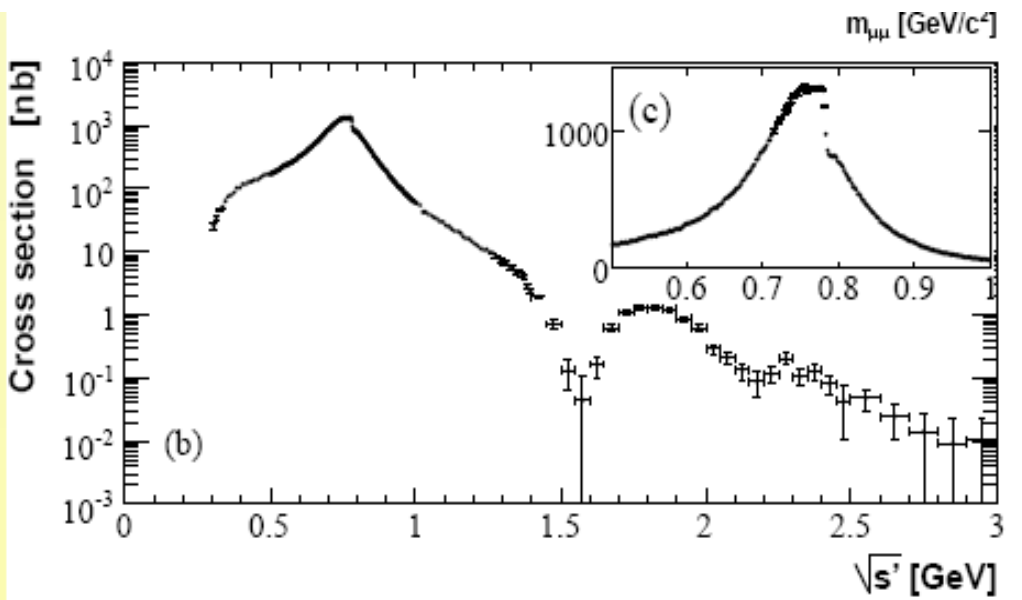


Second regime of annihilation into on-shell mediators (called *secluded*) does not have any restrictions on the size of mixing angle κ.

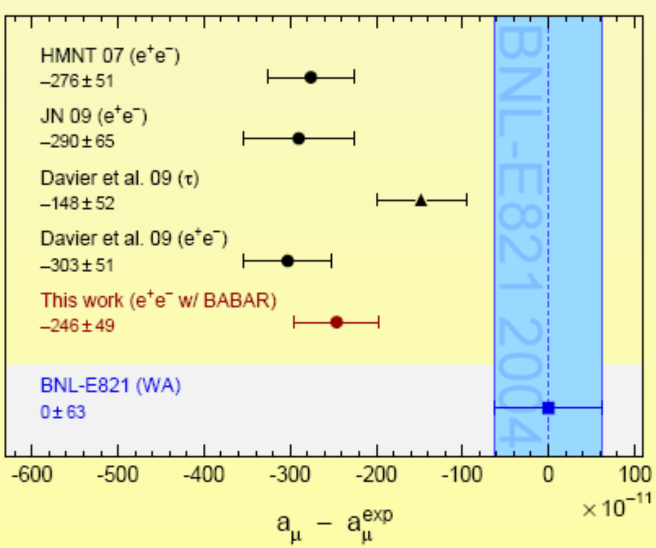
It turns out *this helps* to tie PAMELA positron rise and WIMP idea together.

g-2 of muon

BaBar contribution to the “hadronic piece” of VP diagram



More than 3 sigma discrepancy for most of the analyses. Possibly a sign of new physics, but some complicated strong interaction dynamics could still be at play.



✱ Davier et al. arXiv:0906-5443

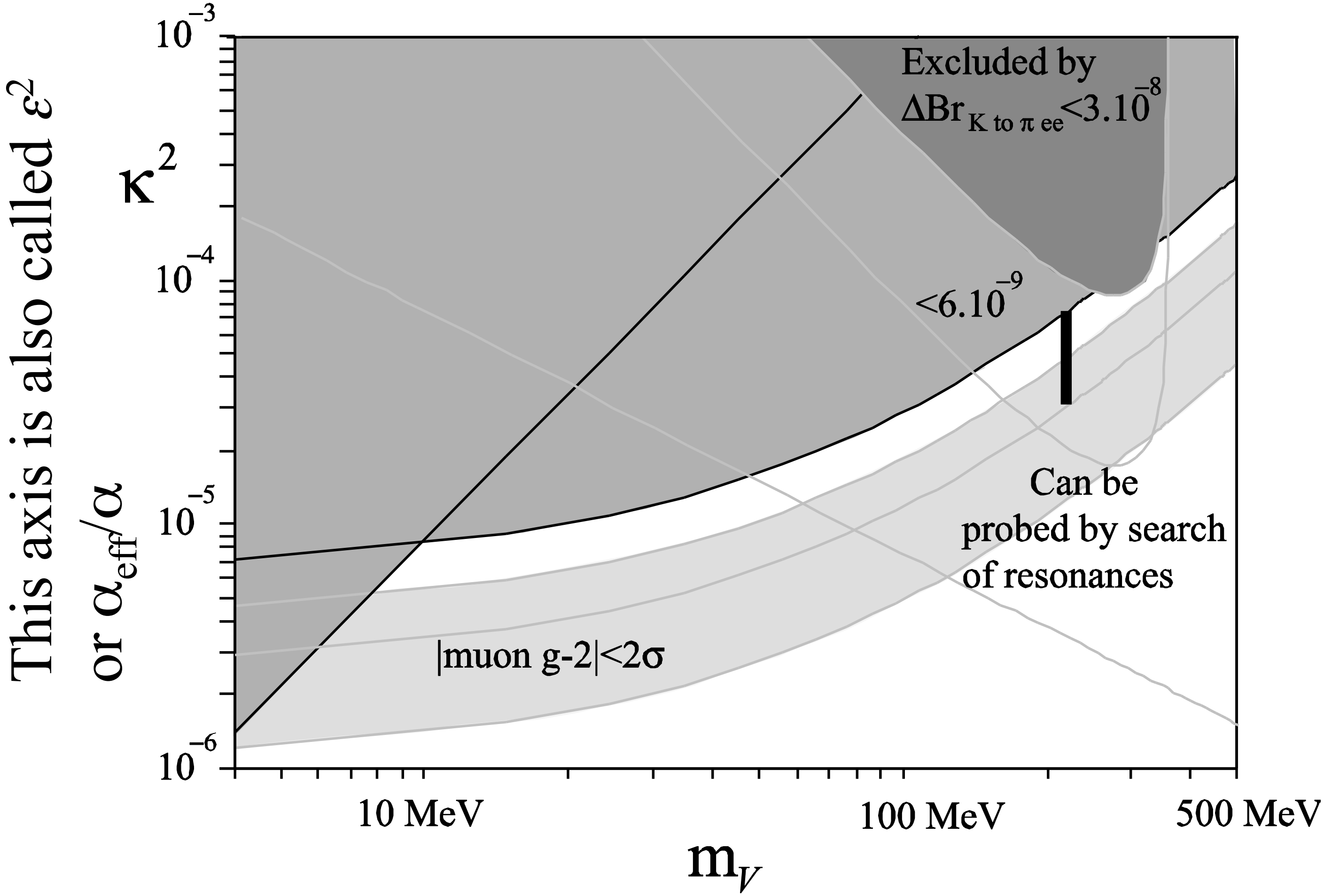
Supersymmetric models with large-ish *tanβ*; light-ish sleptons, and right sign of μ parameter can account for the discrepancy.

Sub-GeV scale vectors can also be at play.

κ-m_V parameter space

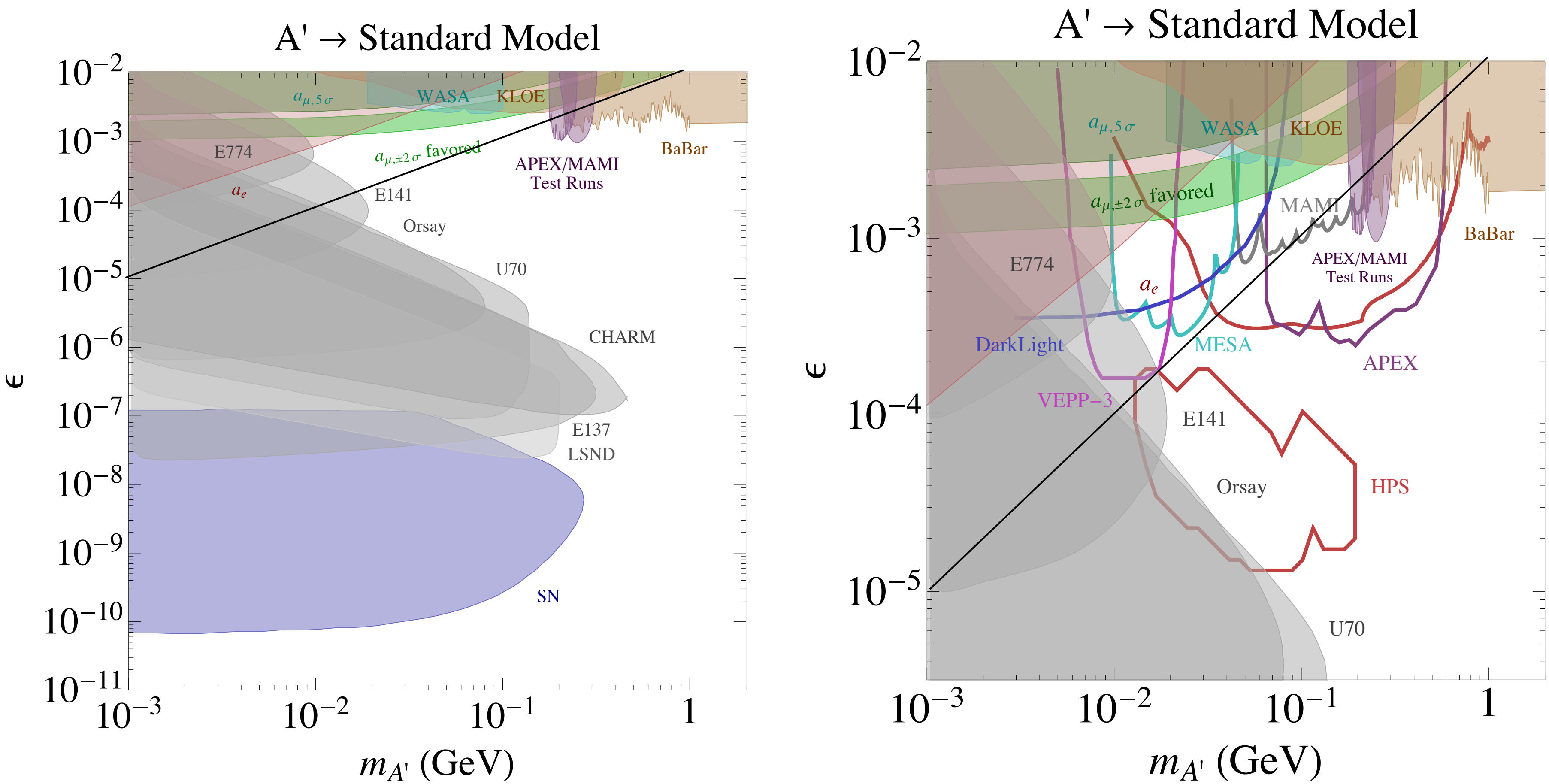
If g-2 discrepancy taken seriously, a new vector force can account for deficit. (Krasnikov, Gninenko; Fayet; Pospelov)
E.g. mixing of order few 0.001 and mass $m_V \sim m_\mu$

MP, 2008



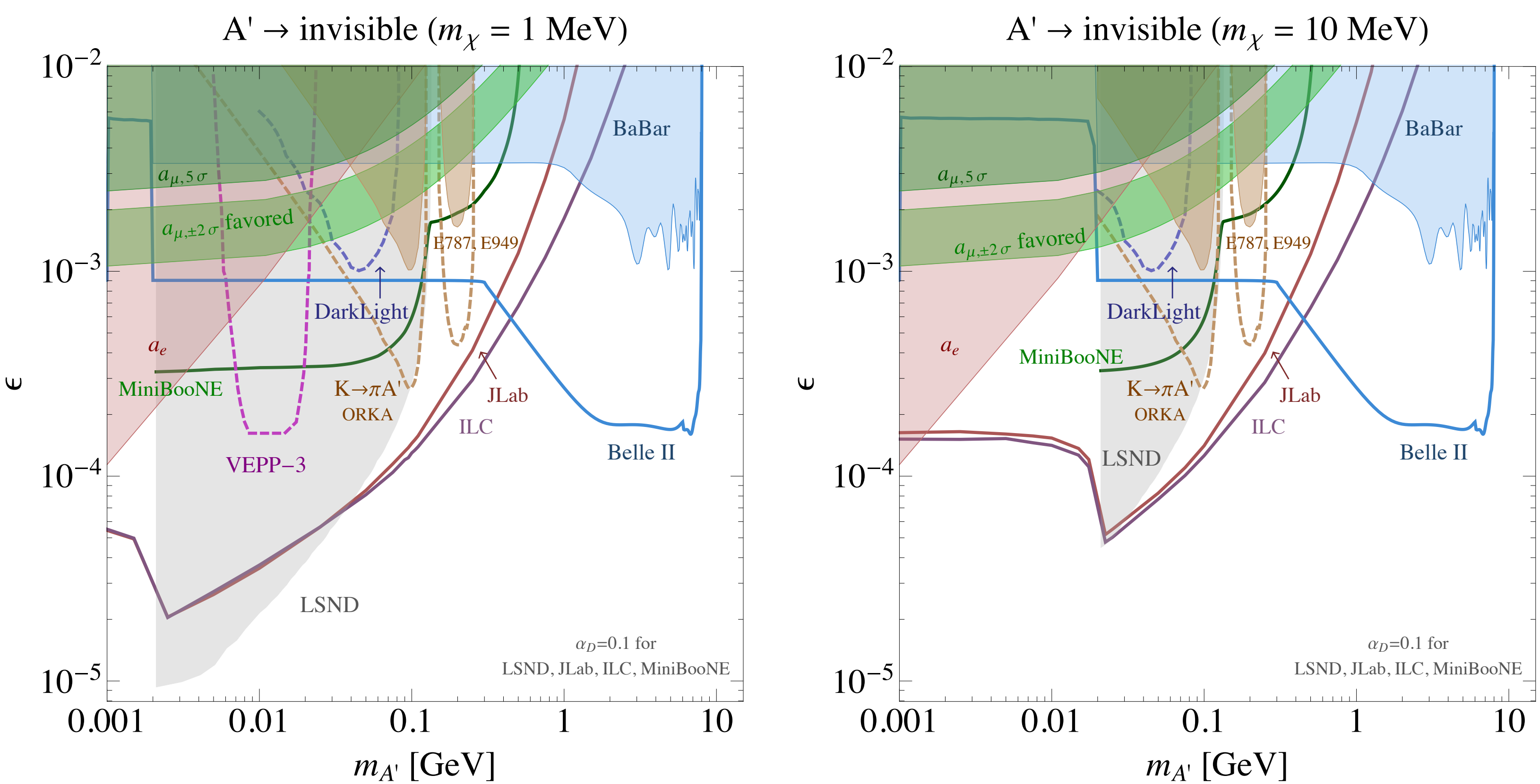
Since 2008 a lot more of parameter space got constrained

κ-m_V parameter space, Essig et al 2013



Dark photon models with mass under 1 GeV, and mixing angles ~ 10^{-3} represent a "window of opportunity" for the high-intensity experiments, and soon the g - 2 ROI will be completely covered. *But what if dark photon decays to light dark matter?*

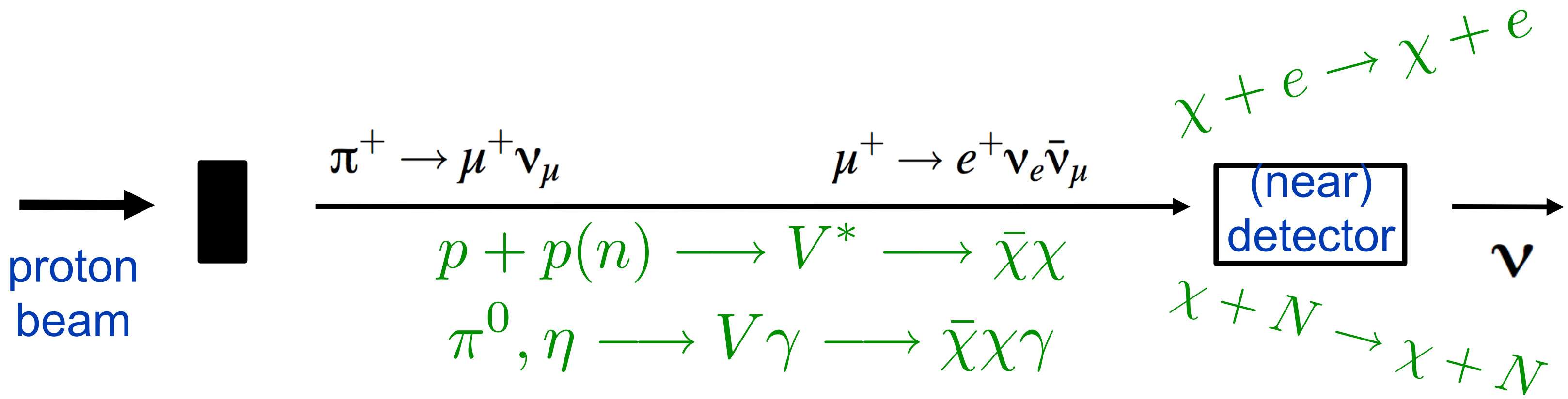
Compilation of current constraints on dark photons decaying to light DM



The sensitivity of electron beam dump experiments to light DM is investigated in Izaguirre, Krnjaic, Schuster, Toro 2013.

Fixed target probes - Neutrino Beams

Proposed in Batell, MP, Ritz, 2009. Strongest constraints on U_F



We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

T2K	MINOS	MiniBooNE
30 GeV protons	120 GeV protons	8.9 GeV protons
(➠ ~5x10^{21} POT)	10^{21} POT	10^{21} POT
280m to on- and off-axis detectors	1km to (~27ton) segmented detector	540m to (~650ton) mineral oil detector

Secured several months of running in 2013-2014!

Light Mass WIMP Searches with a Neutrino Experiment: A Request for Further MiniBooNE Running

September 19, 2012

The MiniBooNE Collaboration

R. Dharmapalan, S. Habib, C. Jiang, & I. Stancu
University of Alabama, Tuscaloosa, AL 35487

R. A. Johnson & D.A. Wickremasinghe
University of Cincinnati, Cincinnati, OH 45221

F.G. Garcia , R. Ford, T. Kobilarcik, W. Marsh,
C. D. Moore, D. Perevalov, & C. C. Polly
Fermi National Accelerator Laboratory, Batavia, IL 60510

J. Grange & H. Ray
University of Florida, Gainesville, FL 32611

R. Cooper & R. Tayloe
Indiana University, Bloomington, IN 47405

G. T. Garvey, W. Huelsnitz, W. Ketchum, W. C. Louis, G. B. Mills,
J. Mirabal, Z. Pavlovic, & R. Van de Water,
Los Alamos National Laboratory, Los Alamos, NM 87545

B. P. Roe
University of Michigan, Ann Arbor, MI 48109

A. A. Aguilar-Arevalo
Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, D.F. México

P. Nienaber
Saint Mary's University of Minnesota, Winona, MN 55987

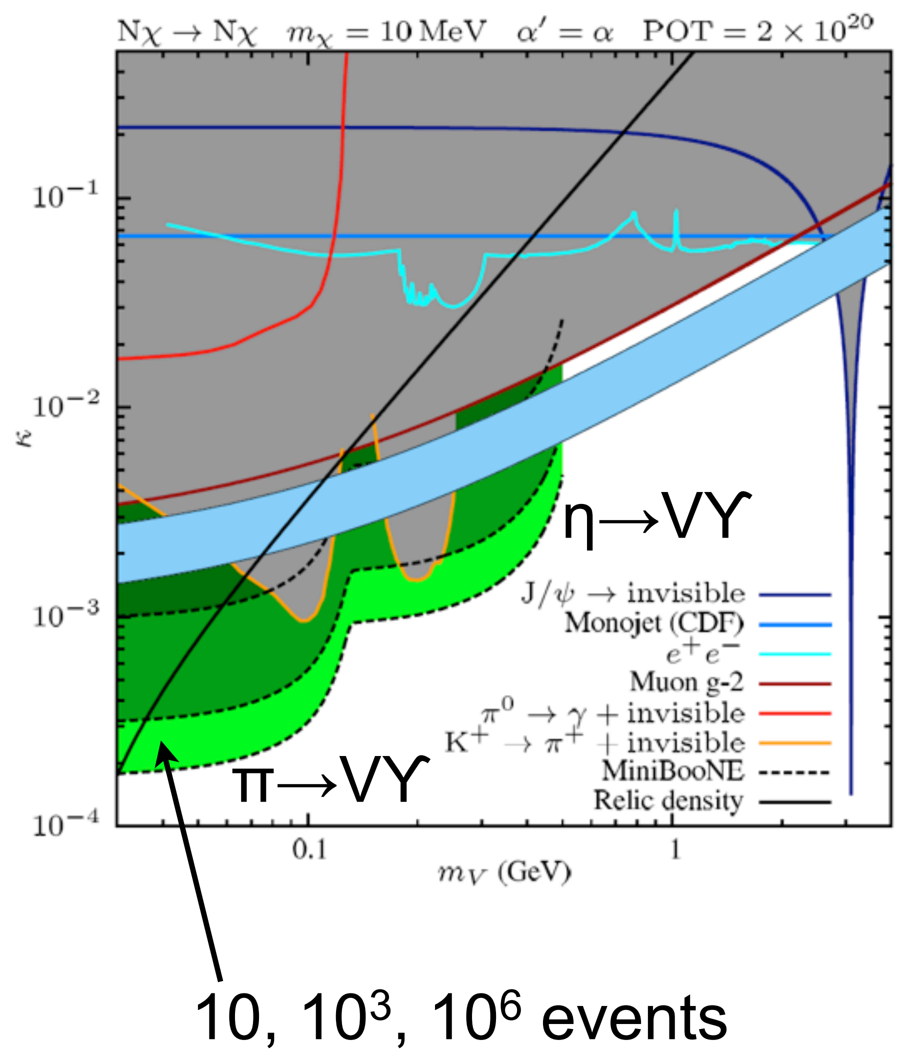
The Theory Collaboration

B. Batell
University of Chicago, IL 60615

P. deNiverville , D. McKeen, M. Pospelov, & A. Ritz
University of Victoria, Victoria, BC, V8N-1M5

Batell, deNiverville, McKeen, MP, Ritz

MiniBooNE sensitivity – quite a bit of new ground can be covered



Other type of dark vector force?

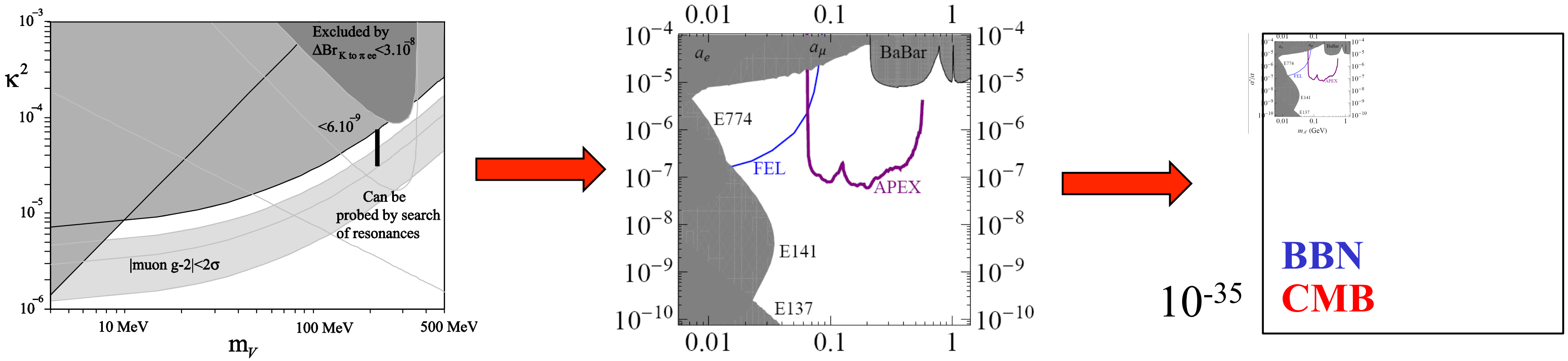
The work on other type of "dark vector forces" is on-going.

1. Batell et al. investigate the sensitivity of MiniBooNE to the "baryonic" portal, or gauged baryon number – this portal is also "flavor-safe".

2. Altmannshofer et al. investigate dark forces coupled to gauged lepton numbers (such as L_μ-L_τ). It turns out that the most sensitive probe of such models is the well-forgotten (25 yr old) observation of muon pair-production by the muon neutrinos, $Z+\nu \rightarrow Z + \mu^+ \mu^- +\nu$, the so-called muonic trident.

Mini-conclusions: systematic studies of all possibilities for the intensity frontier physics, searching for light weakly coupled states, is gathering momentum. There is still plenty of "low hanging fruits", and in many instances sensitivity reach can be advanced by many orders of magnitude by a relatively modest theoretical and experimental investment.

Very [very] dark photons



The Universe itself is an *active detector*! Unlike astrophysics which presents challenging backgrounds, pre-galactic cosmology is relatively *simple*, and thanks to recent advances, allows for precision tests.

Take a dark photon with $M_V \sim$ MeV, $\kappa \sim 10^{-18}$, or $\boldsymbol{\alpha_{eff} = 10^{-38}}$. Cross section for producing such a particle is $\sigma \sim 10^{-65}$ cm^2 or so.

Even a "Project XXX" would not help… Yet we have evidence of $T \sim$ MeV (through BBN) in the early Universe.

Fradette, MP, Pradler, Ritz, *to appear soon.* Some of these constraints are pointed out in Postma, Redondo, 2008.

Produced early – decays late

- The production cross section is ridiculously small, but in the early Universe at T > m_V , in fact, *every colliding pair of particles can produce such Vectors*, and there is a lot of time available for this.

- Once produced such particles *live for a very long time*, and decay in the "quiet" Universe, depositing non-thermal amounts of energy and changing physics of primordial matter after recombination.

- Precision determination of optical depth during the CMB, position of Doppler peaks and the slope of the Silk diffusion tale provide tight restrictions on the amount of energy injected.

- Due to BBN we also have a pretty good evidence that the Universe in fact once was at least T ~ a few MeV hot…..

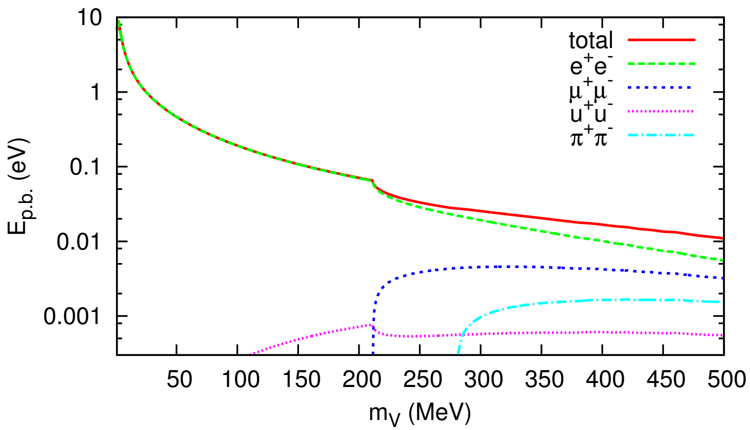
Filling out details….

- Lifetime against the decay to electron-positron pairs

$$\tau_V \simeq \frac{3}{\alpha_{\rm eff} m_V} = 0.6 \text{ mln yr} \times \frac{10\,{\rm MeV}}{m_V} \times \frac{10^{-35}}{\alpha_{\rm eff}}$$

- $e^+e^- \rightarrow V$ in the early Universe leads to the energy stored per baryon

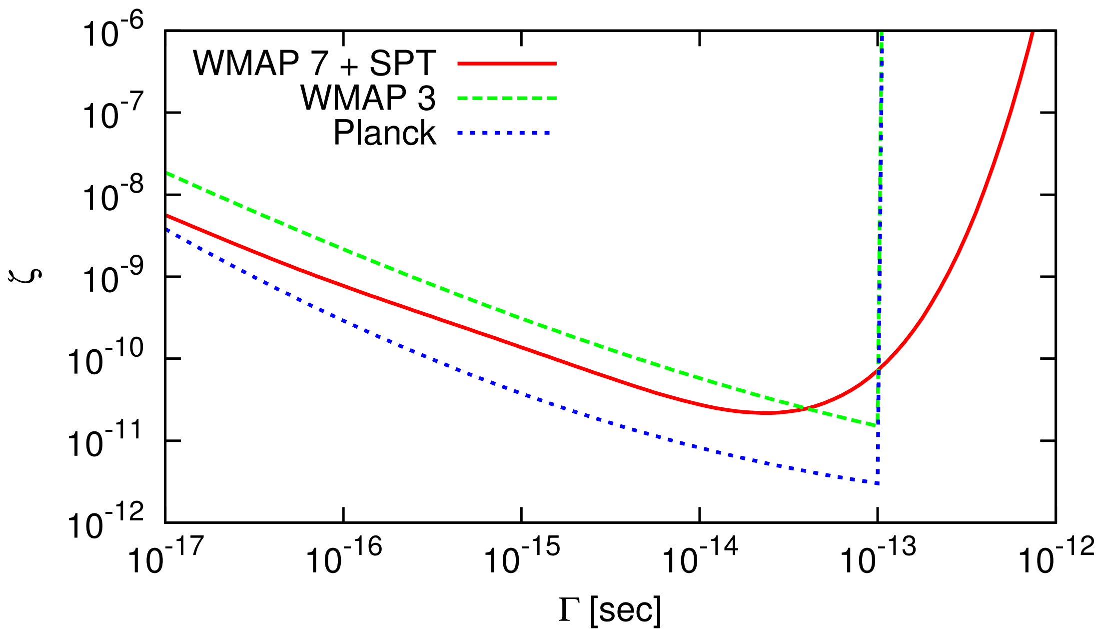
$$E_{\rm p.b.} \sim \frac{m_V \Gamma_{\rm prod} H^{-1}_{T=m_V}}{n_{b,T=m_V}} \sim \frac{0.1\alpha_{\rm eff} M_{\rm Pl}}{\eta_b} \sim \alpha_{\rm eff} \times 10^{36}\,{\rm eV}$$



for $\Gamma_V^{-1} = 10^{14}$s.

- Once injected back to the medium via $V \rightarrow e^+e^-$ ~ 1/3 of the stored energy leads to ionization. E.g. 1 eV p.b. recreates $X_e \sim$ few 10^{-2}.

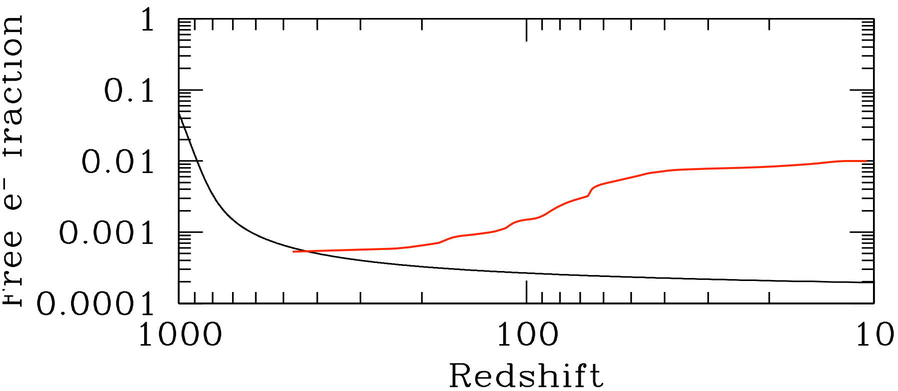
Constraints from WMAP

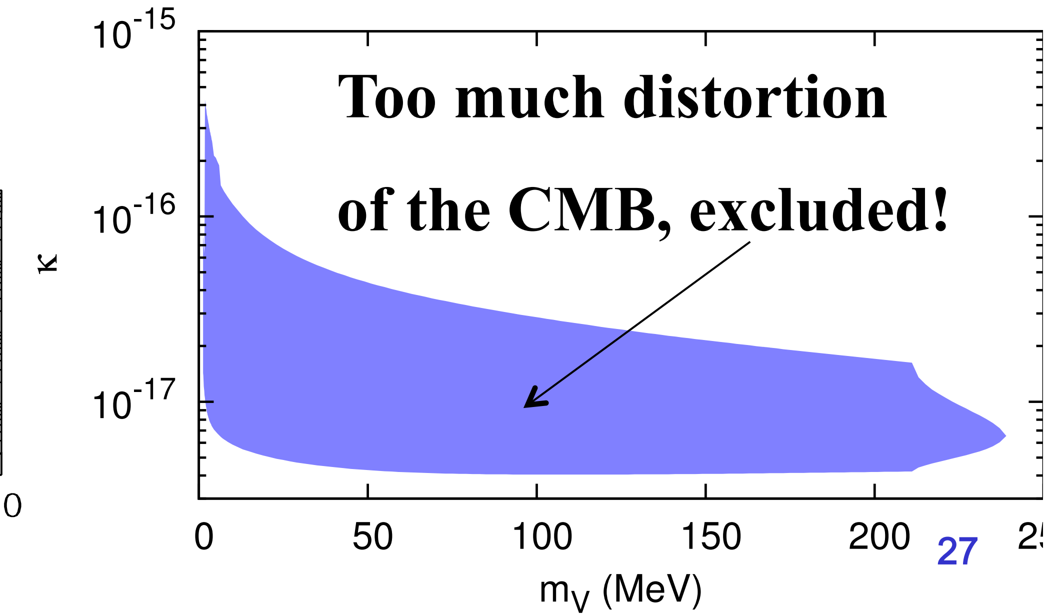


$$\zeta = \frac{f}{3}\frac{\Omega_V}{\Omega_b} = \frac{f}{3}\frac{E_{\rm p.b.}}{m_p}.$$

Fradette et al, 2014

to appear





<BB> = T or "T-like" modes ?

1. *Every big discovery follows by the period of trying to understand the result.* E.g. excess of events around 125 GeV → Evidence of a new resonance → Higgs-like properties of the resonance → dropping "-like" after lots of tests. In the process you rule out competitors such as KK-graviton, techni-pion, etc [no matter how creepy they are]. Same process should occur with the discovery of B-modes, but is not happening yet to the fullest.

2. *The minimal interpretation of B-modes are tensor perturbations*, the remnants of inflation that occurred with $H_{infl}=10^{14}$ GeV. Well, it poses a lot of questions to anyone who tries to play with some physics that has fundamental scale below 10^{14} GeV.

3. One can provide new mechanisms of B-mode generation with a low inflationary scale, e.g. $H_{infl} \sim 10^{10}$ GeV (MP, Ritz, Skordis, 2008). View it as a competitive explanation of Bicep observations, and try to rule it out from data!

Two-axion model

- Two-axion model is like that. One axion becomes a QCD axion, and the other one remains massless,

$$\left(\frac{a_1}{2g_1}+\frac{a_2}{2g_2}\right)G_{\mu\nu}\tilde{G}^{\mu\nu}+\left(\frac{a_1}{2f_1}+\frac{a_2}{2f_2}\right)F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\to \mathcal{L}_{\mathrm{QCD}a}+\frac{a}{2f_a}F_{\mu\nu}\tilde{F}^{\mu\nu},$$

- Coupling constant is given by

$$f_a^{-1}=(g_2/f_2-g_1/f_1)/\sqrt{g_1^2+g_2^2}.$$

Fluctuating pseudoscalar driven by inflation

The model:

$$\mathcal{L}_{everything} = \mathcal{L}_{SM+gravity} + \mathcal{L}_{inflation} + \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{2f_a}F_{\mu\nu}\tilde{F}_{\mu\nu}$$

[Can be viewed as a generic consequence of two QCD axions.

Massless field *a* receives [random, Gaussian, nearly flat-spectrum] fluctuations during inflation, $\delta a \sim H_{infl}/(2\pi)$.

Rotation of polarization plane after travelling from point 1 to point 2 is

(Harrari, Sikivie; Carroll; Lue, Wang, Kamionkowski…)

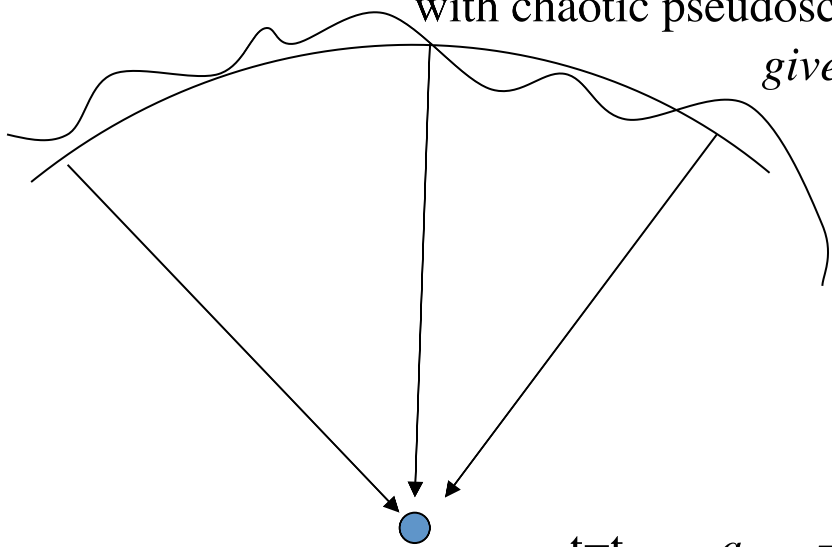
$$\psi = \frac{a_1 - a_2}{f_a}$$

$$\langle EE \rangle \to \langle BB \rangle; \qquad \langle TB \rangle = \langle EB \rangle = 0$$

The measure of the r.m.s. angular rotation is $\delta a \sim H_{infl}/(2\pi f_a)$ Log z

Propagation of CMB from the LSS

Surface of Last Scattering
with chaotic pseudoscalar profile $t=t_{LSS}$, a_{LSS} *is given by inflation*.



$t=t_{today}$, $a_{today}=0$.

Polarization of arriving to us CMB photons is randomly rotated by $\Delta\psi(n) = A_{LSS}(n)=a_{LSS}(n)/f_a$.

For convenience, we introduce c_a

$$c_a = \left(\frac{H}{2\pi f_a}\right)^2, \quad |\Delta\psi| \sim \sqrt{c_a}.$$

Since f_a > 10^{11} GeV is a mild constraint, H ~ 10^10 GeV or below can generate BB

Master formula for <BB> calculation

MP, Ritz, Skordis, 2008

$$C_{Bl} = \frac{1}{2l+1}\sum_m \langle a^*_{Blm} a_{Blm}\rangle = \frac{4(4\pi)^3}{2l+1}\frac{(l-2)!}{(l+2)!}$$

$$\times \sum_{m,l_1,l_2} (2l_1+1)(2l_2+1)\begin{pmatrix} l & l_1 & l_2 \\ 0 & 0 & 0 \end{pmatrix}^2$$

$$\times \int k^2 \underline{P_\Phi} q^2 \underline{\underline{P_A}}\, dk dq |\Delta_{l_1 l_2 m}(k,q)|^2,$$

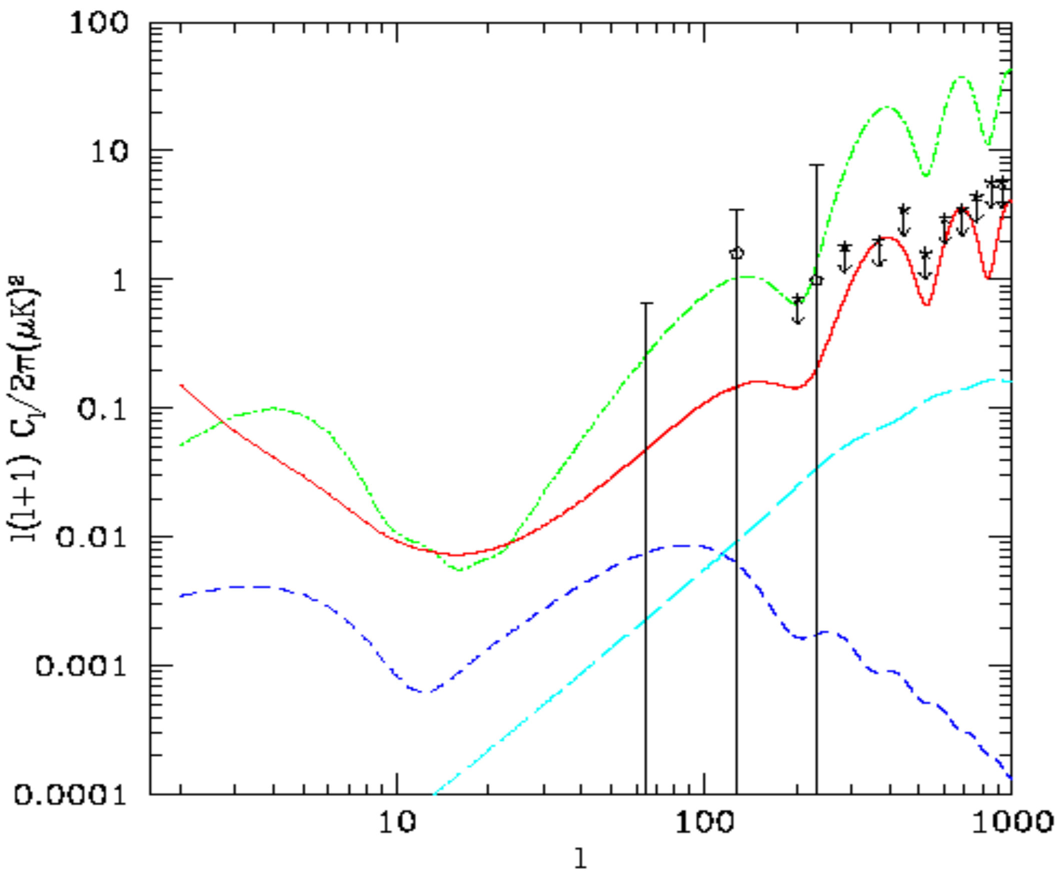
with the generalized transfer function,

$$\Delta_{l_1 l_2 m}(k,q) = \frac{3}{4}\int_0^{\tau_0} d\tau g(\tau) j_{l_1}(x) j_{l_2}(y)$$

$$\times \left(\frac{(l_1+2)!}{(l_1-2)!}\frac{1}{x^2} - m^2\right)\Delta_A(\tau,q)\Pi(\tau,k).$$

2008 limits

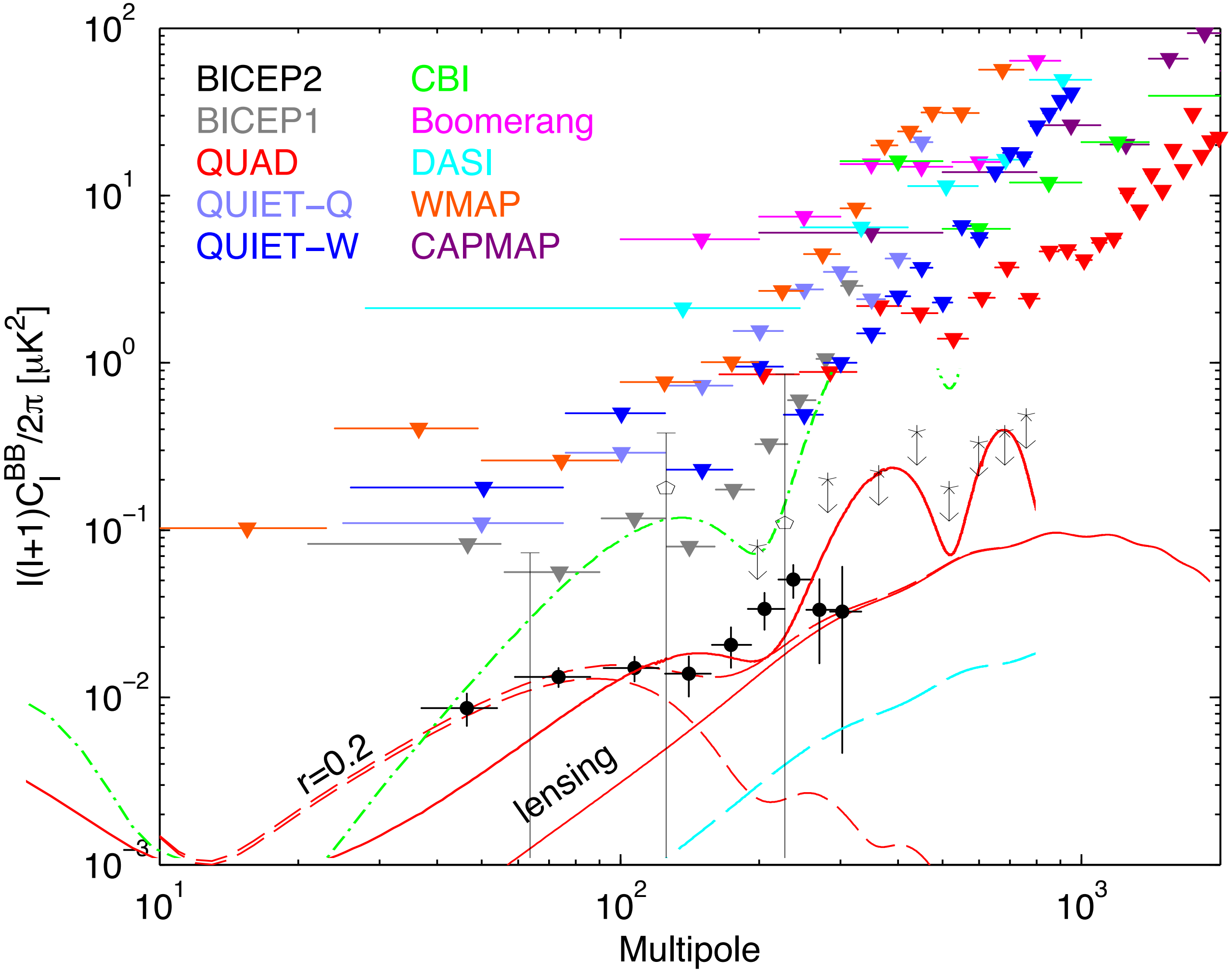
Numerical Results and comparison with experiment



Points: upper limits from WMAP5 and QUaD

Green: EE; Red: BB with c_a =0.004; Dark blue: BB from gravity waves with r=0.14; light blue: BB lensing background . **CAN WE MATCH IT ONTO BICEP???**

The moment of truth



Inflationary pseudoscalar fluctuations do not give a good fit to Bicep data(too low l<100) !!! So, it more "T-like" and not at all "*a*-like".

Conclusion

1. Intensity frontier – "orthogonal" to energy frontier direction – can and should look for light weakly coupled states.

2. Search for "dark photons" – the simplest model of an additional U(1) has been intensified over the years, fueled by its possible connection to several "anomalies" in particle physics and cosmology. New results brought new constraints, but no independent hints on a signal. "g-2" region is [almost] covered.

3. "Very dark photons" with mixing angles ~ 10^{-17} is an example of unique sensitivity the precision CMB brings to our field.

4. Recent discovery of the B-modes – if confirmed as coming from the tensor perturbations generated during inflation with $H_{\rm infl} \sim 10^{14}$ GeV – will limit any massless pseudoscalar field to photons as $f_{a\gamma\gamma} > 10^{15}$ GeV (compare with direct CAST bound of 10^{11} GeV). *It is also important to rule chaotic rotation of E to B as the sole source of* C^{l}_{BB}.

Astrophysical motivations: 511 keV line

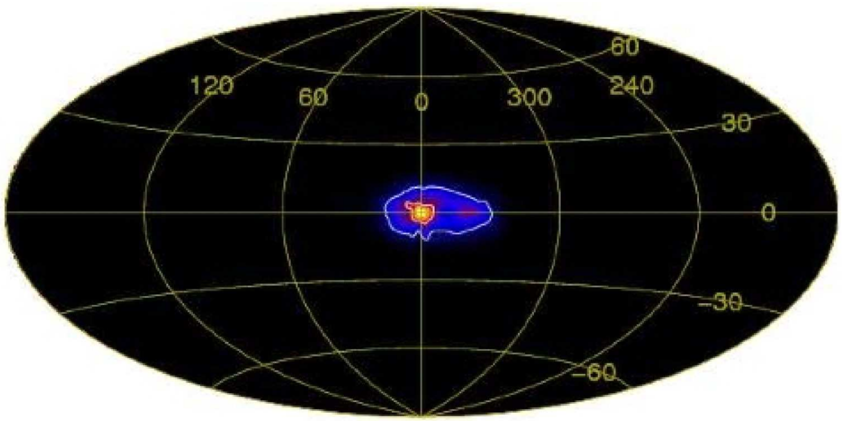


FIG. 4 511 keV line map derived from 5 years of INTEGRAL/SPI data (from Weidenspointner *et al.*, 2008a).

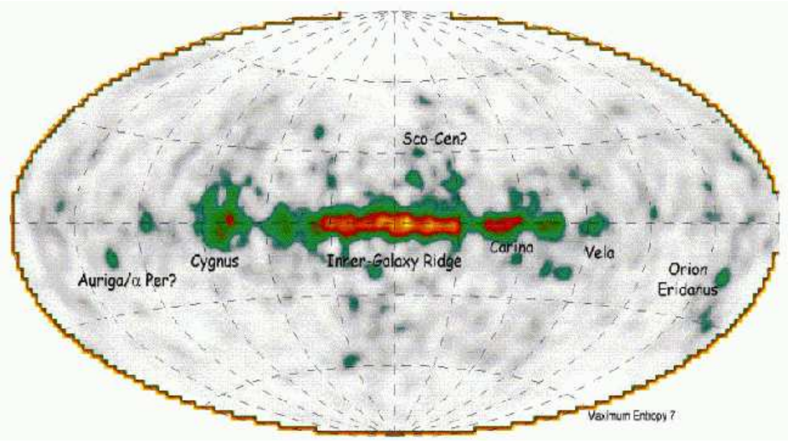
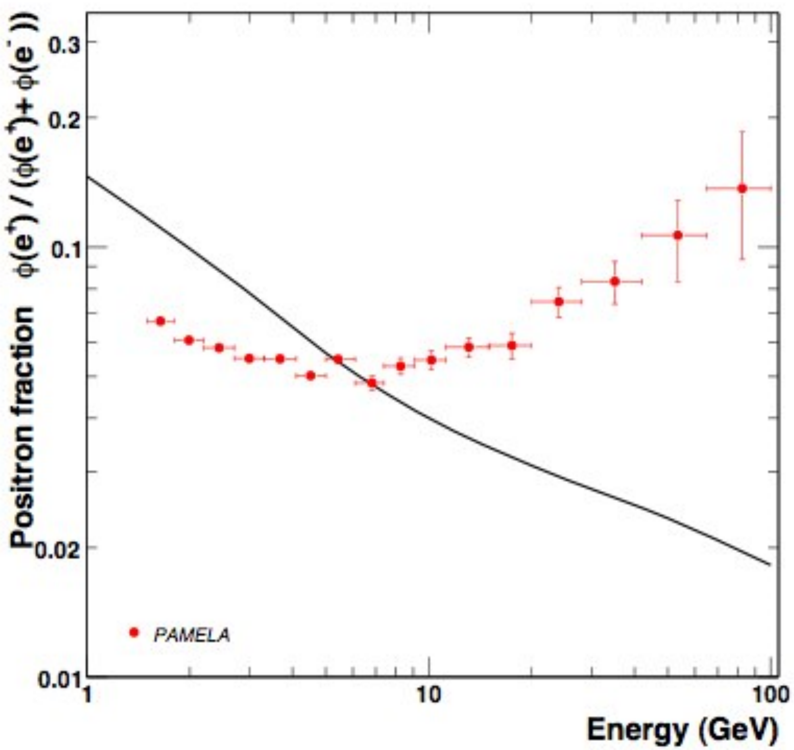


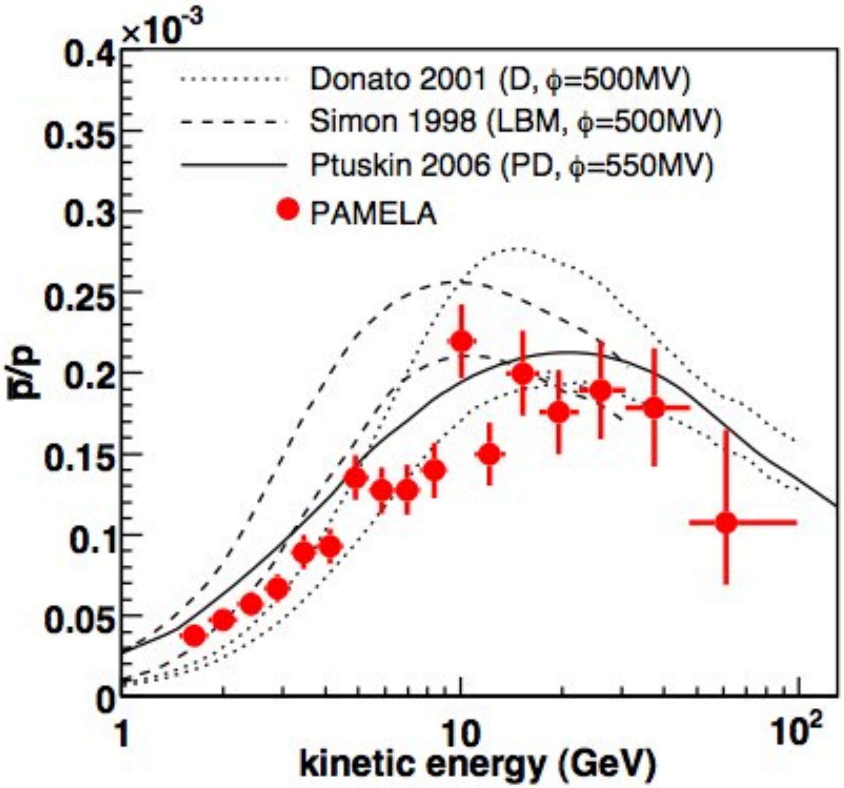
FIG. 7 Map of Galactic ^{26}Al γ-ray emission after 9-year observations with COMPTEL/CGRO (from Plüschke *et al.*, 2001).

There is a lot more positrons coming from the Galactic Center and the bulge that expected. The emission seems to be diffuse.

1. Positrons transported into GC by B-fields?
2. Positrons are created by episodic violent events near central BH?
3. Positrons being produced by DM? Either annihilation or decay?

PAMELA positron fraction





No surprises with antiprotons, but there is seemingly a need for a new source of positrons!

This is a "boost" factor of 100-1000 "needed" for the WIMP interpretation of PAMELA signal. E.g. SUSY neutralinos would not work, because <σv > is too small. Enhancing it "by hand" does not work because WIMP abundance goes down. Dark forces allow bridging this gap due to the late time enhancement by Coulomb (Sommerfeld).