# Beyond and Below the Standard Model: Light Exotic New Physics

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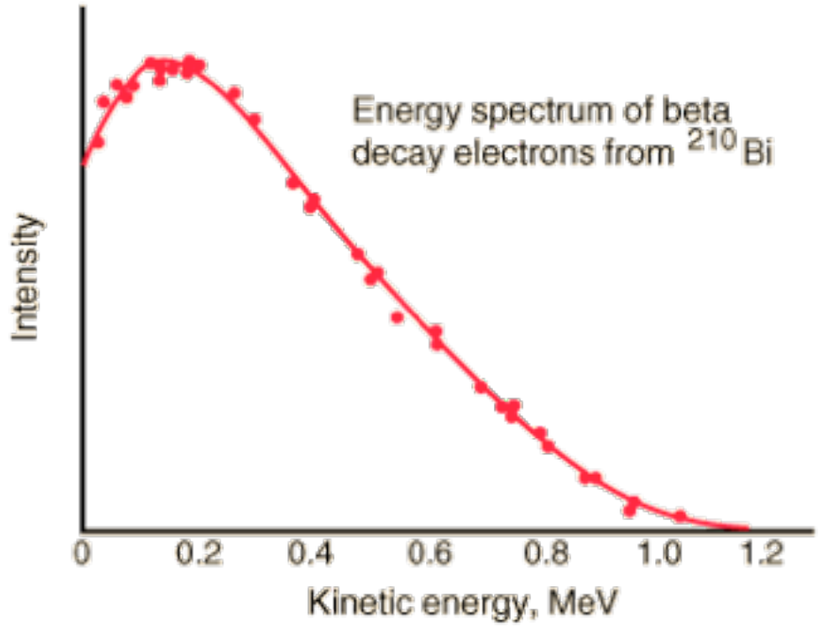
# History lesson - 1930s:

- Back then, the "Standard Model" was photon, electron, nucleons
- Beta decay: $n \to p + e^-$




Continuous spectrum!

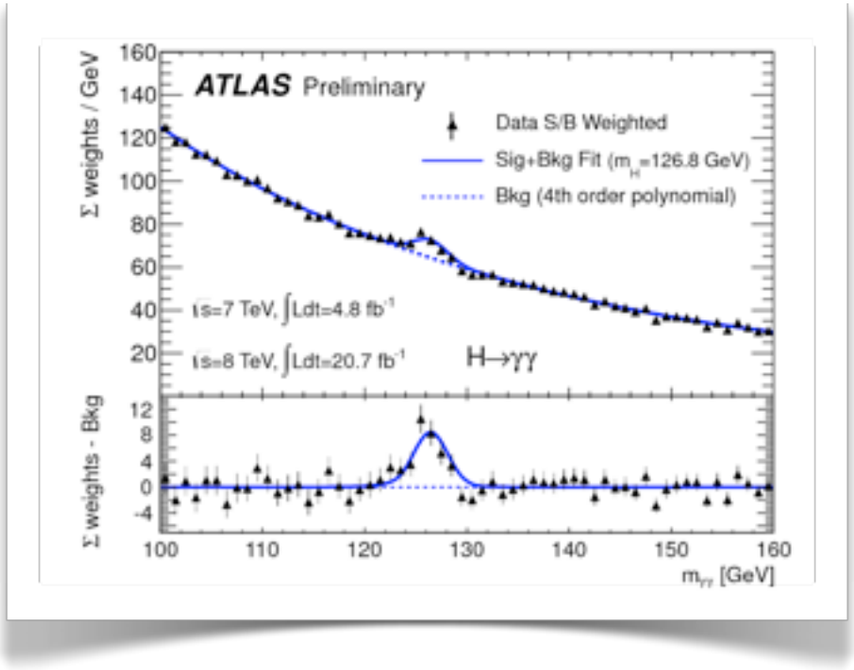
- Pauli proposes a radical solution - the neutrino!

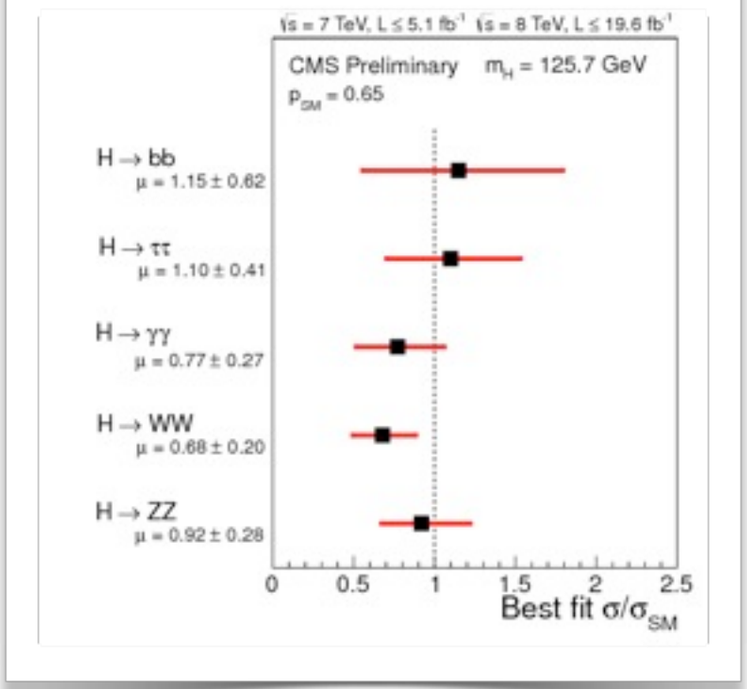
$$n \to p + e^- + \bar{\nu}$$

- Perfect example of a "hidden sector"
  - neutrino is electrically neutral (QED gauge singlet)
  - very weakly interacting and light
  - interacts with "Standard Model" through "portal" - $(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu \nu)$

# Today, 2014 - Where are we?

- Higgs!
- Triumph of the Standard Model!




- Still, many reasons to believe there is new physics

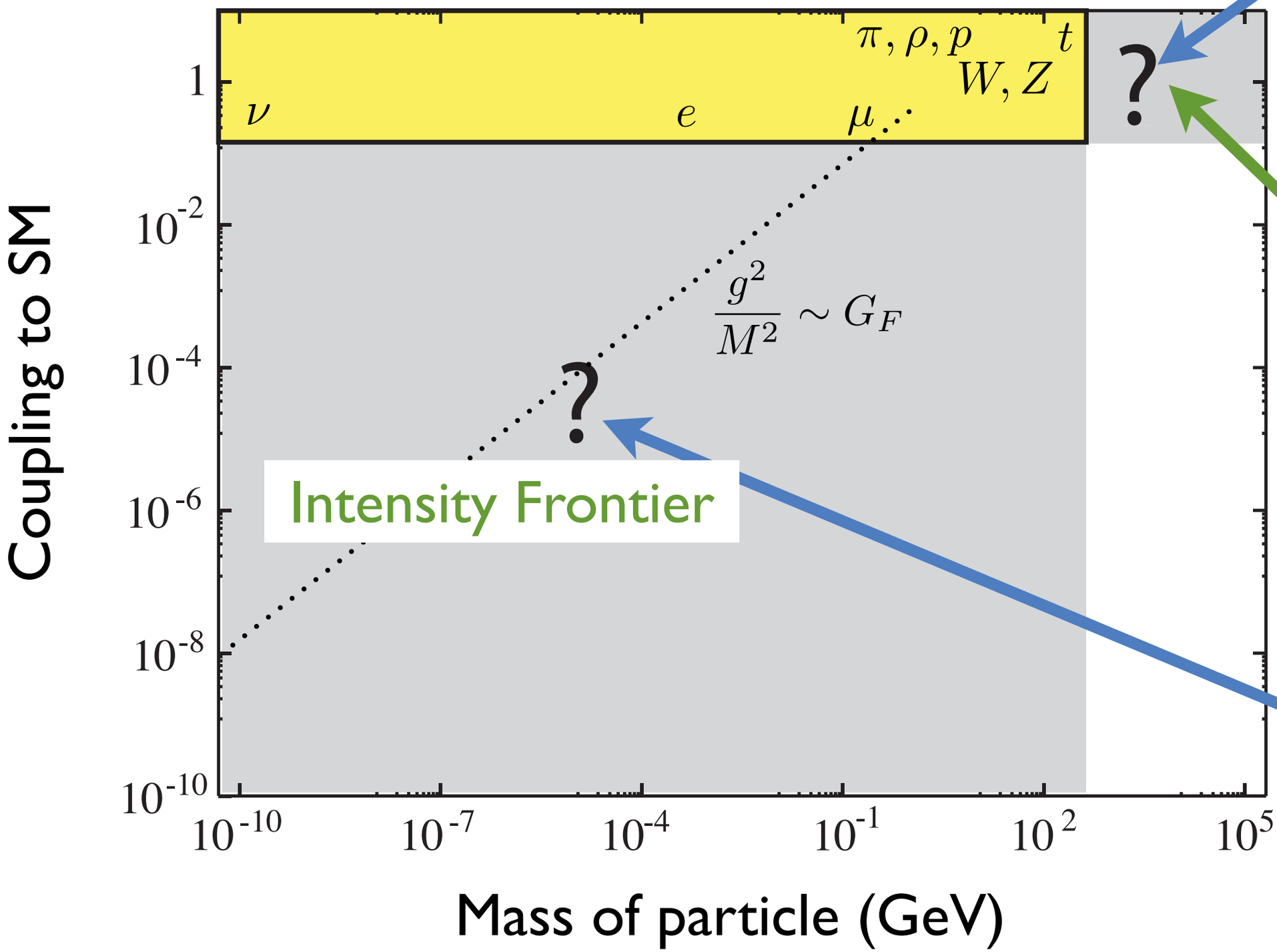
Theoretical: naturalness (Higgs, CC), flavor, Strong CP, Unification, Gravity ...

Empirical: Dark Matter, Neutrino Oscillations, Baryon Asymmetry

- Unfortunately, there are no guarantees of discovery
- All searches for new physics are now fishing expeditions!

# Where is the new physics?

EWSB, Hierarchy
WIMP DM ...




Energy
Frontier
- LHC

RH neutrinos
Axion
Dark Matter
Hidden sector
...

# Light, Exotic, and Motivated!

Lensing, rotation curves, structure, CMB... → Dark Matter

Neutrino oscillations → Right Handed Neutrinos

Strong CP → Axion

Supersymmetry → Gravitino
SUSY hidden sectors

...

# The scale of new physics

Theoretical hints (naturalness) - unambiguously points towards new scale

Hierarchy problem → $v \sim 100\,\mathrm{GeV}$

Cosmological Constant → $\rho_{\mathrm{vac}}^{1/4} \sim 10^{-3}\,\mathrm{eV} \quad (m_\nu \sim 0.1\,\mathrm{eV})$

Empirical hints - no firm prediction for the new physics scale!

Matter-Antimatter Asymmetry → ?

Dark Matter → ?

Neutrino mass → ?

We must search High and Low for New Physics!

# Portals - an EFT approach

$$LHN \qquad \text{Neutrino portal}$$

$$(\mu S + \lambda S^2) H^\dagger H \qquad \text{Higgs Portal}$$

$$-\frac{\kappa}{2} B_{\mu\nu} V^{\mu\nu} \qquad \text{Vector Portal}$$

- Only three renormalizable portals - can be generated at a high scale
- Respect approximate symmetries of the Standard Model
  - Flavor, Parity, CP - allows for relatively large couplings to be viable

# Portals - an EFT approach

$LHN$ Neutrino portal

$(\mu S + \lambda S^2) H^\dagger H$ Higgs Portal

Focus on vector portal in this talk

$-\frac{\kappa}{2} B_{\mu\nu} V^{\mu\nu}$ Vector Portal

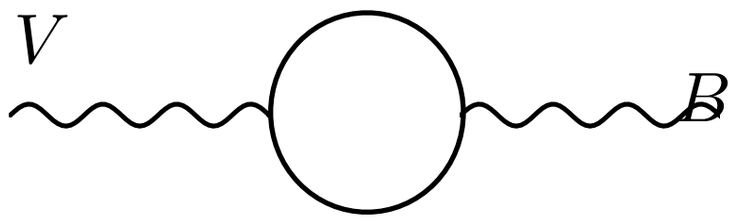
- Only three renormalizable portals - can be generated at a high scale
- Respect approximate symmetries of the Standard Model
  - Flavor, Parity, CP - allows for relatively large couplings to be viable

# Vector Portal

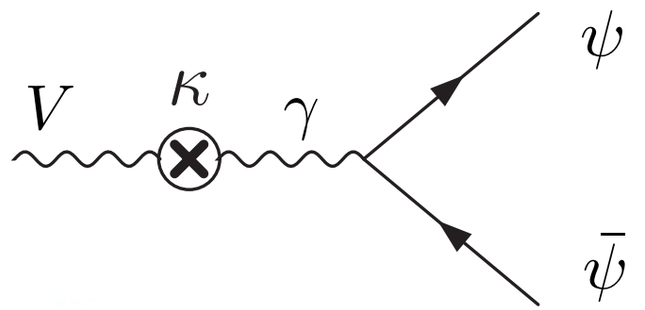
$$-\frac{\kappa}{2} B_{\mu\nu} V^{\mu\nu}$$

Holdom

Mixing parameter can be generated radiatively at one or more loops; expected size ~ $10^{-3}$ or smaller




If dark U(1) is broken visible matter picks up a milli-dark charge.




$$\mathcal{L} \supset \kappa V_\mu [-c_w J^\mu_{EM} + s_w (1 - m_Z^2/m_V^2)^{-1} J^\mu_Z].$$

Mass can be generated through dark Higgs or Stueckelberg mechanism

Goodsell et al

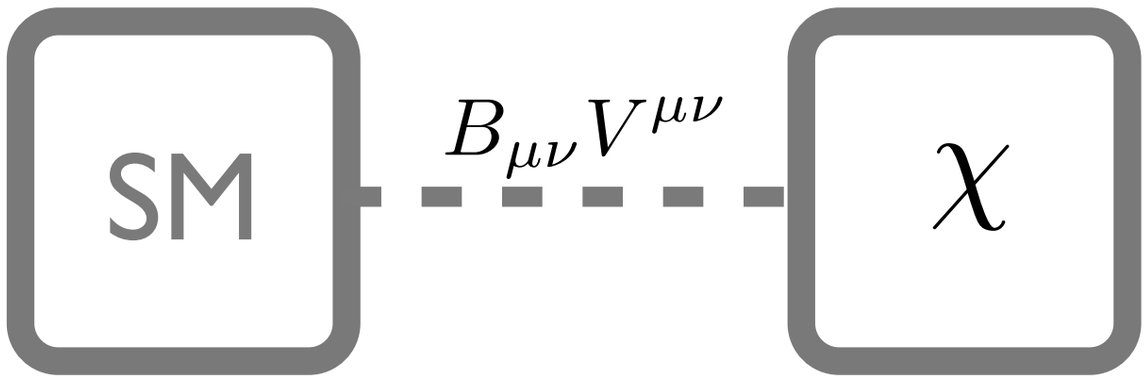
In SUSY theory - mass scale tied to the weak scale as

$$m_V \sim \sqrt{\kappa}\, m_Z$$

- Suggests light, (sub-)GeV scale dark photons

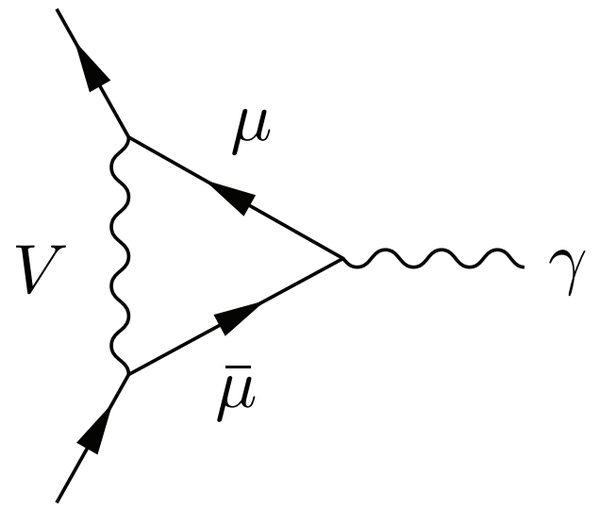
Arkani-Hamed, Weiner;
Cheung et al;
Morissey et al;

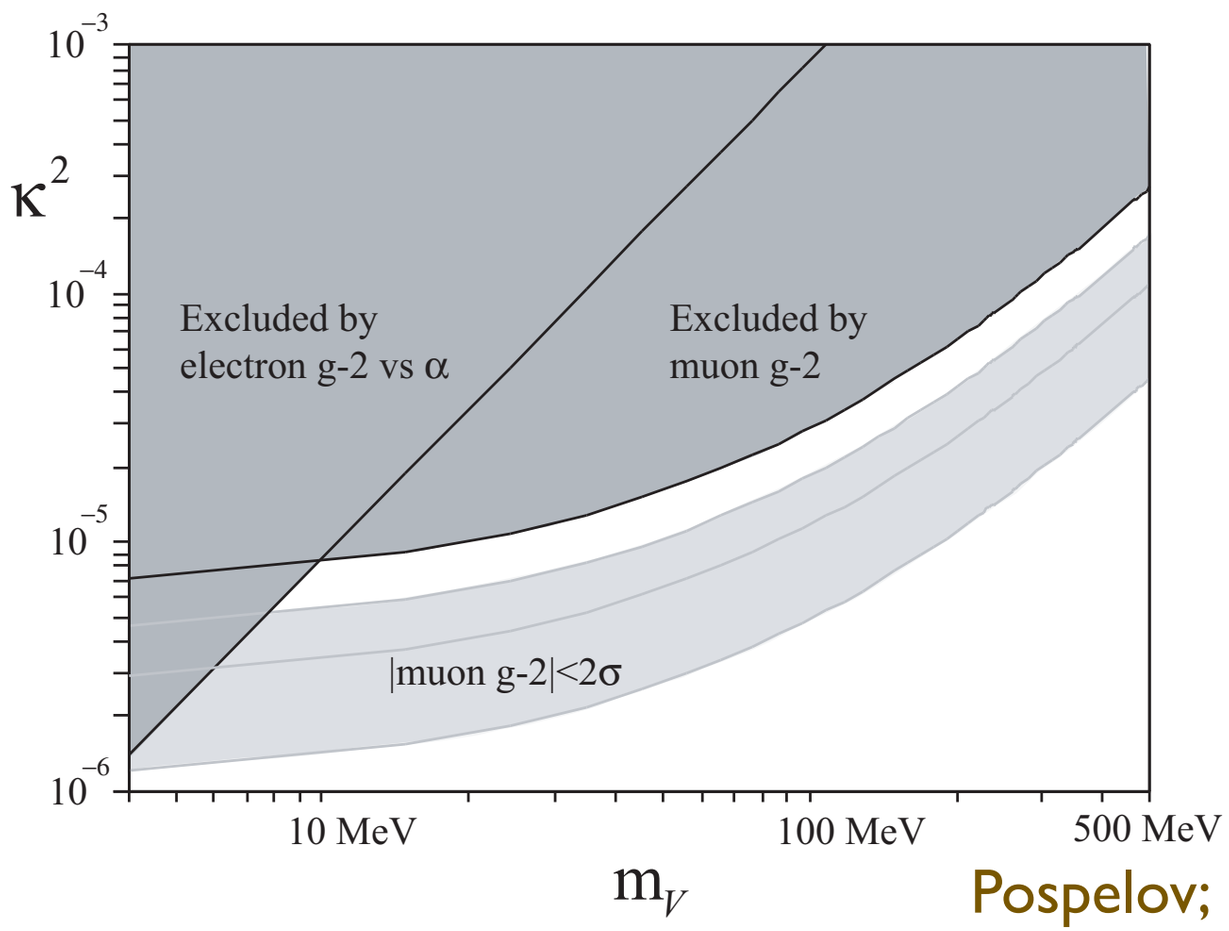
Can serve as a portal to Dark Matter




Dark photon (or cousins) often motivated by anomalies:

Example: Muon Anomalous Magnetic Moment (~ $3\sigma$ )

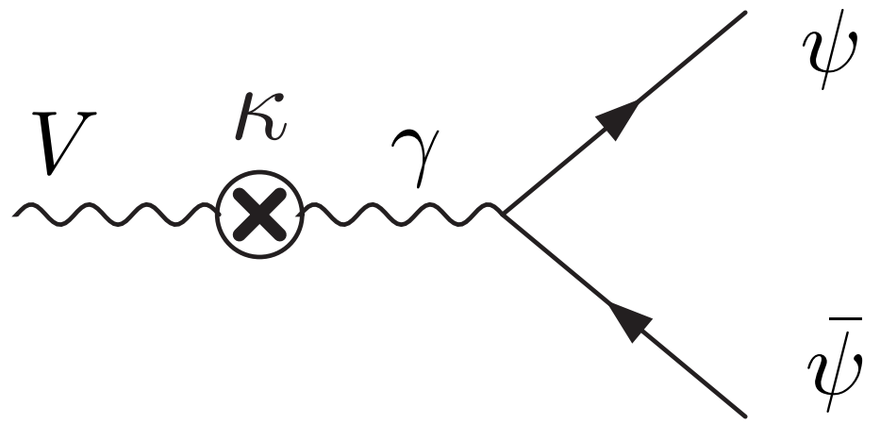


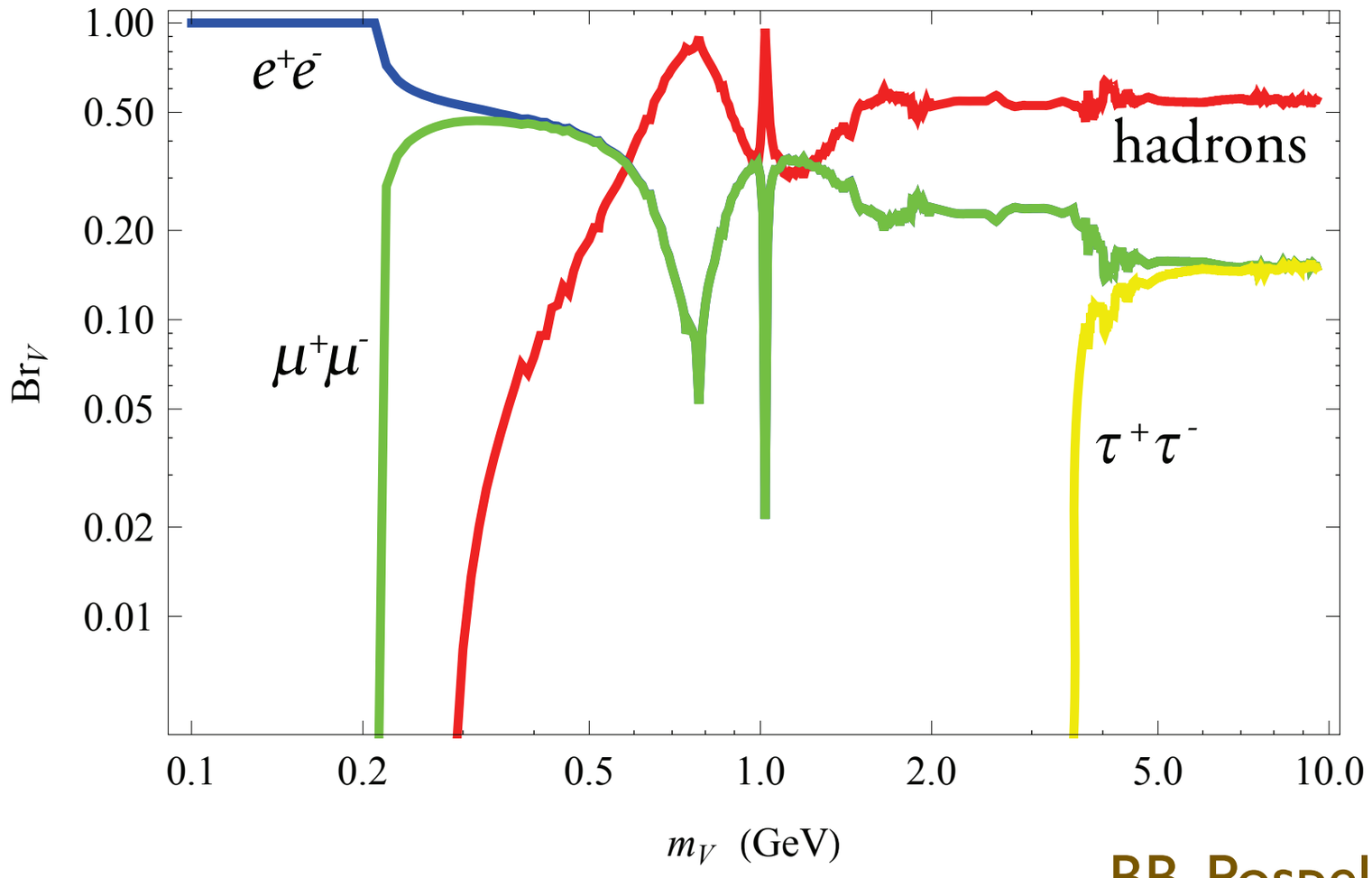




Pospelov;
Bohm, Fayet

# Dark photon decays

- governed by EM form factor
- significant branching to leptons

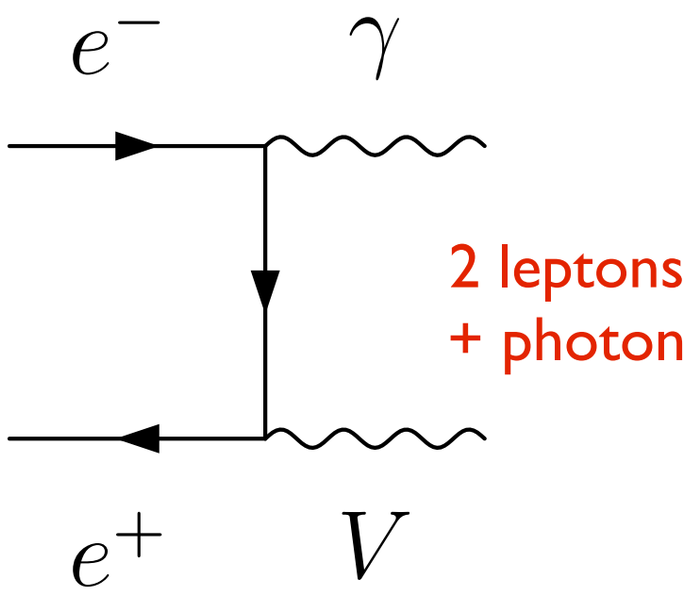


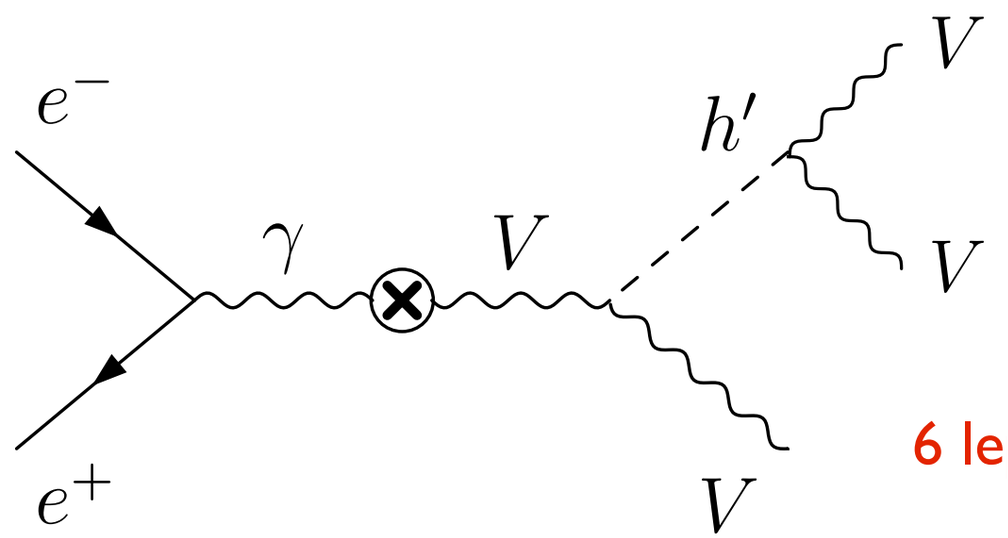

BB, Pospelov, Ritz

# Signatures at low-energy e+e- colliders

BB, Pospelov, Ritz;
Essig Schuster, Toro;
Reece Wang;

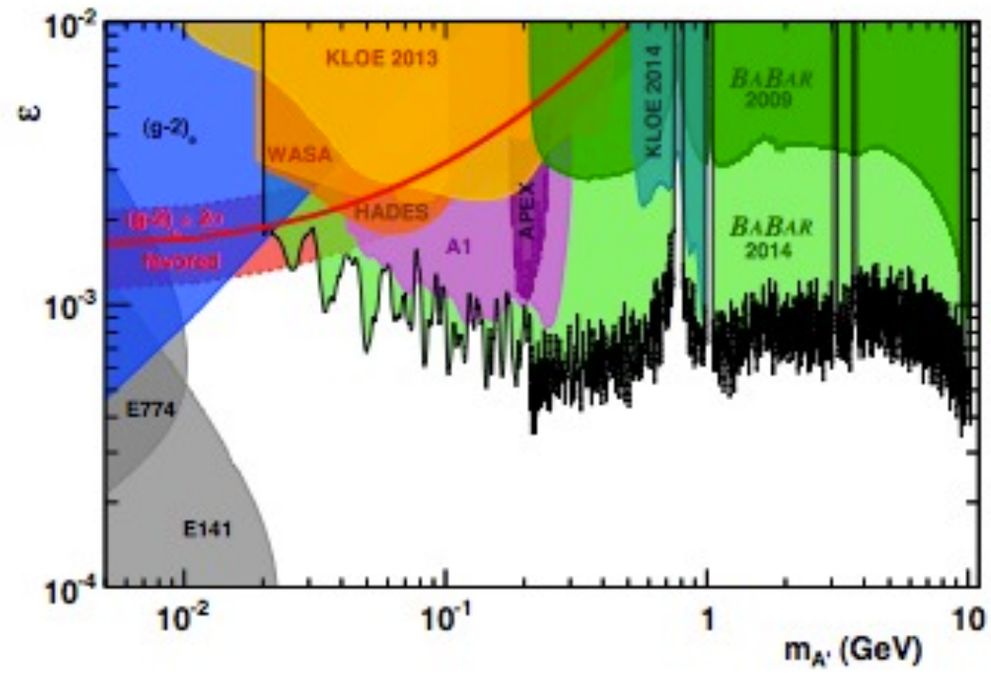



2 leptons
+ photon

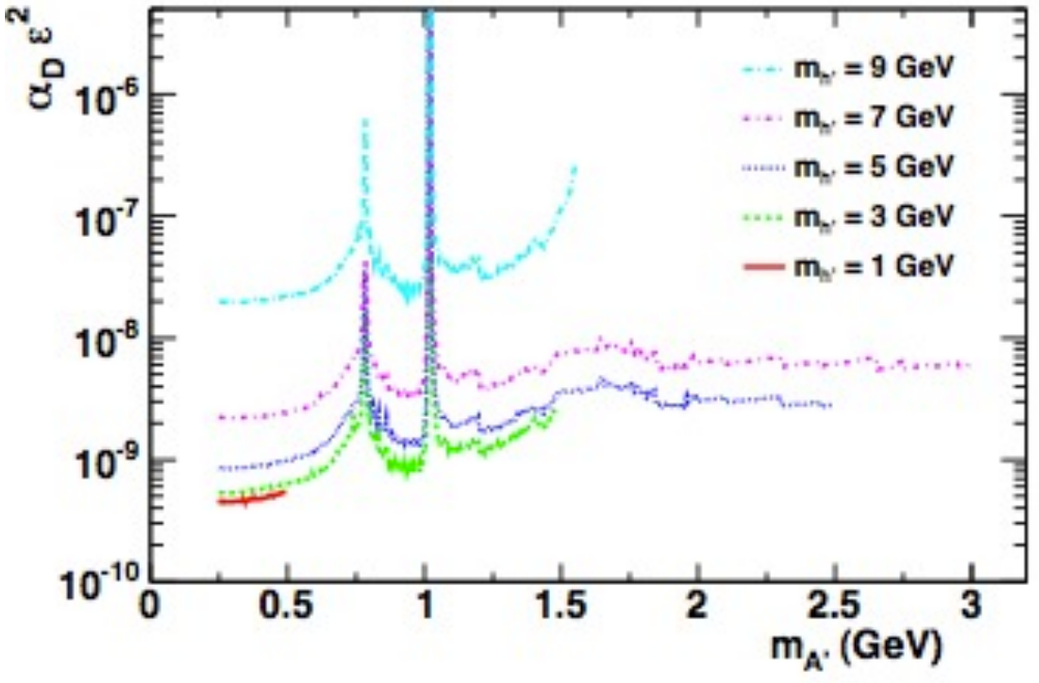



6 leptons

# Dark photon searches at BaBAR



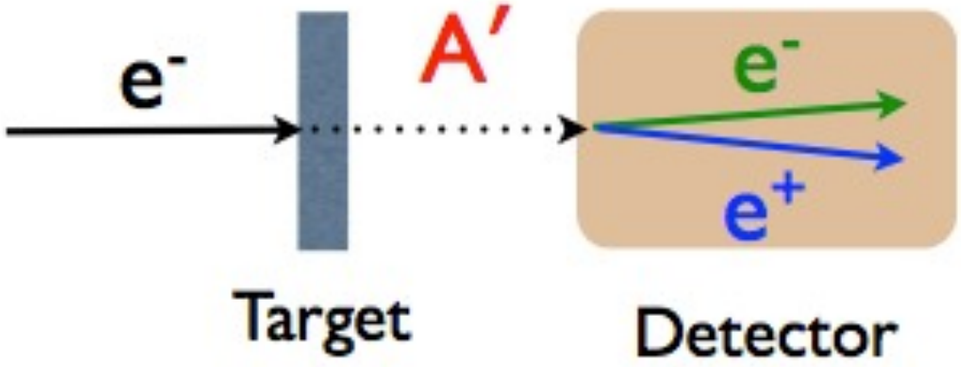

[BaBAR, PRL 113 (2014)]




[BaBAR, PRL 108 (2012)]

# Signatures at high intensity fixed target experiments

Bjorken et al;,
Andreas et al;
and others



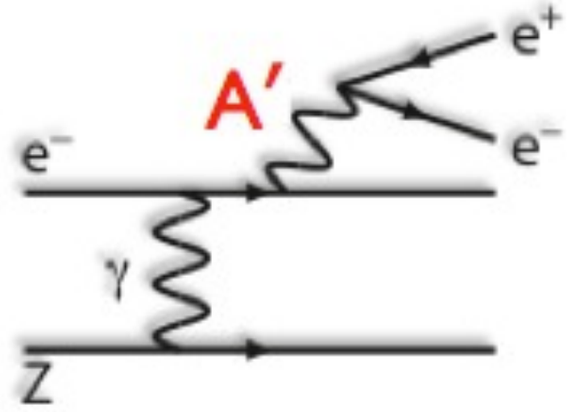
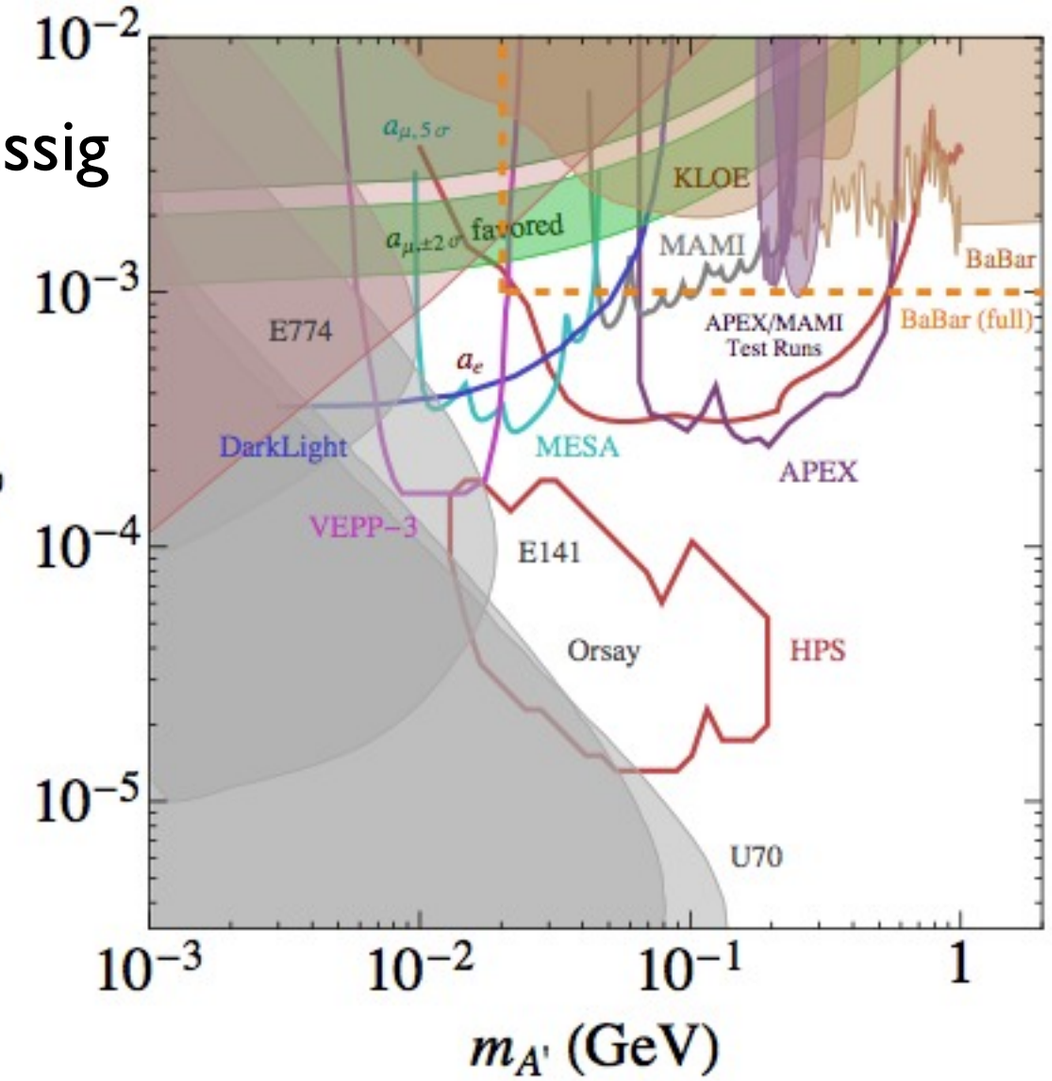




Fig. from R. Essig




- look for a resonance
or displaced vertex

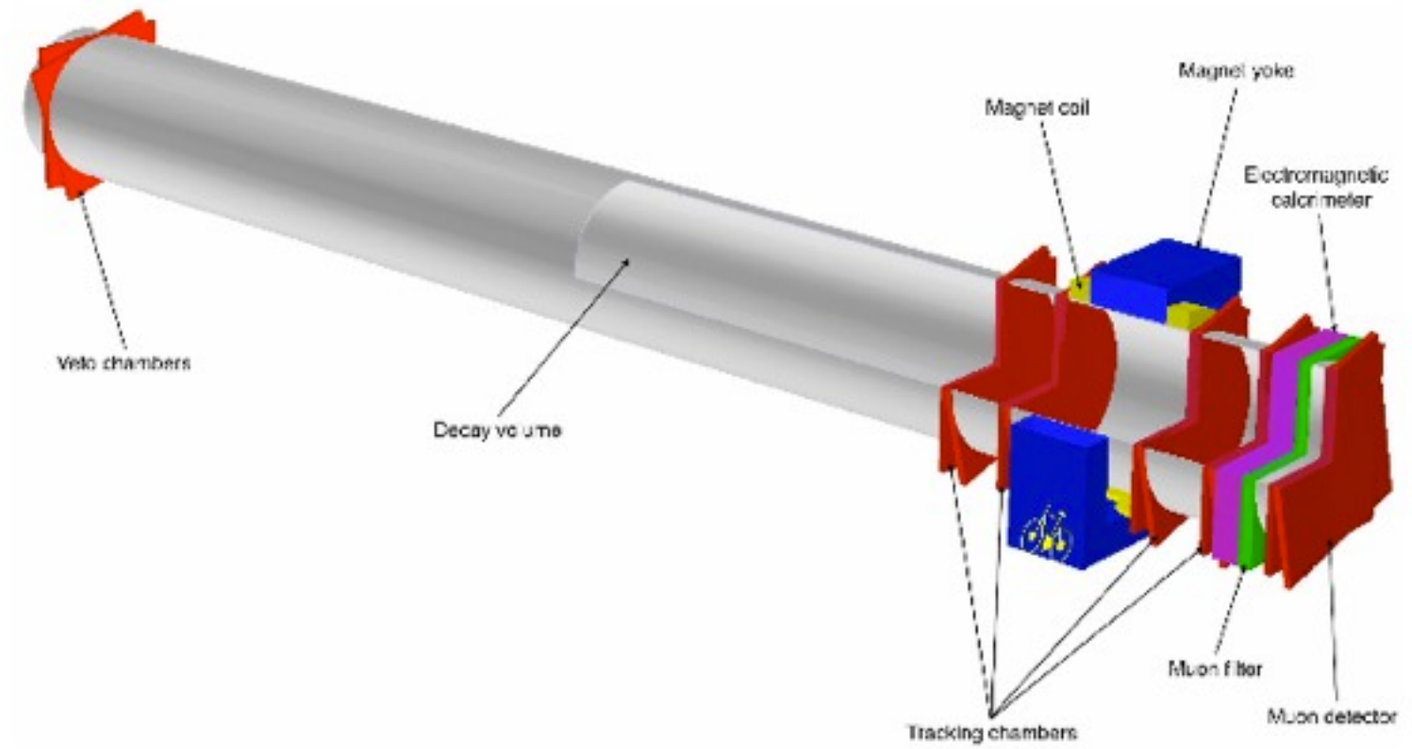
- Current/planned experiments (APEX,HPS,MAMI,DarkLight, VEPP-3, MESA...) will cover a lot of new ground!

# SHiP experiment (Search for Hidden Particles) http://www.cern.ch/ship

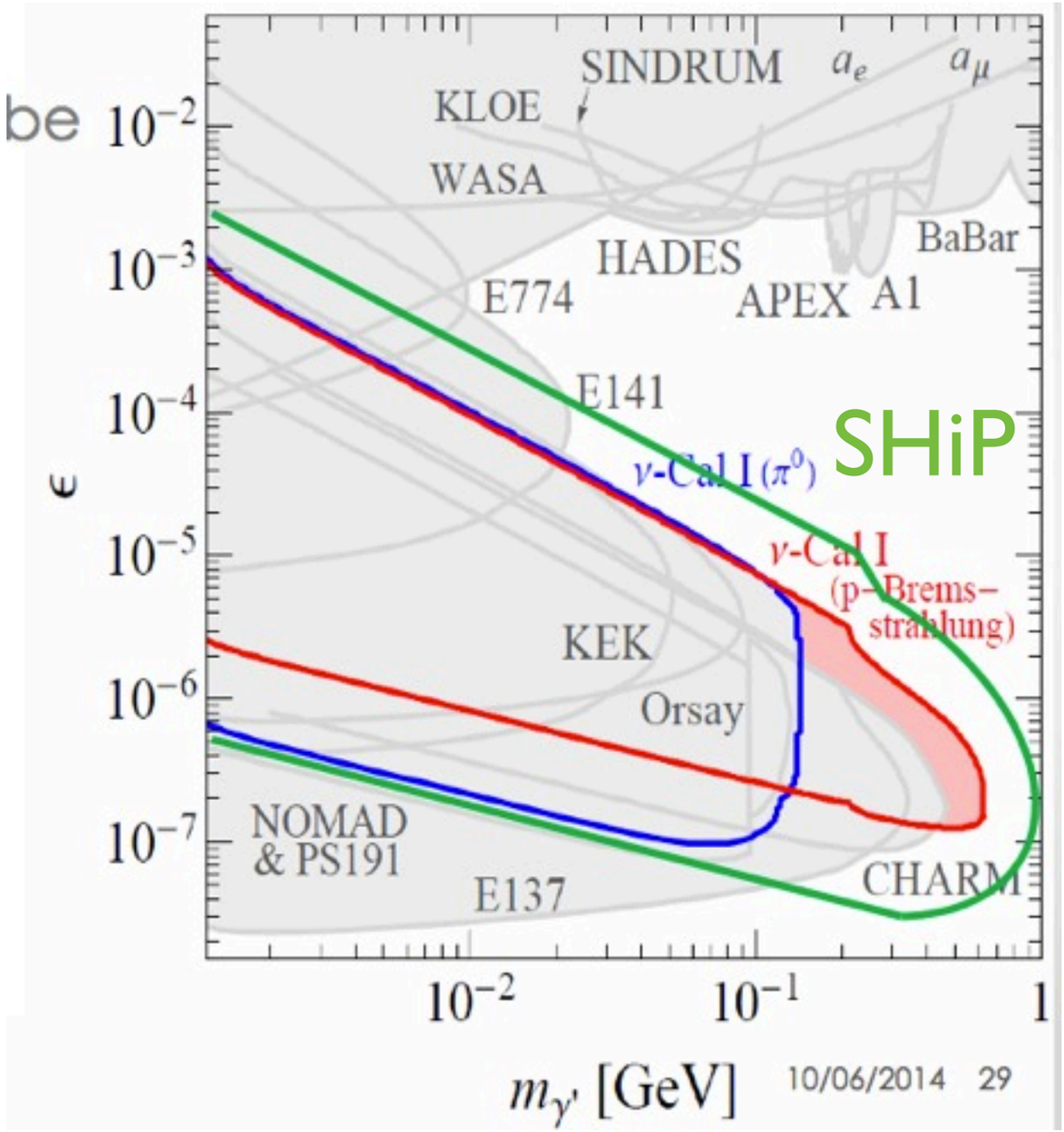
- New Fixed target facility proposed at CERN

- 400 GeV protons, ~$10^{20}$ protons-on-target

- Powerful capability to search for weakly interacting, long-lived particles that decay visibly



# SHiP sensitivity to dark photons




talk by J. Brunner
1st SHiP collaboration meeting

Impressive sensitivity at high mass, and small mixing!

# Summary of different channels

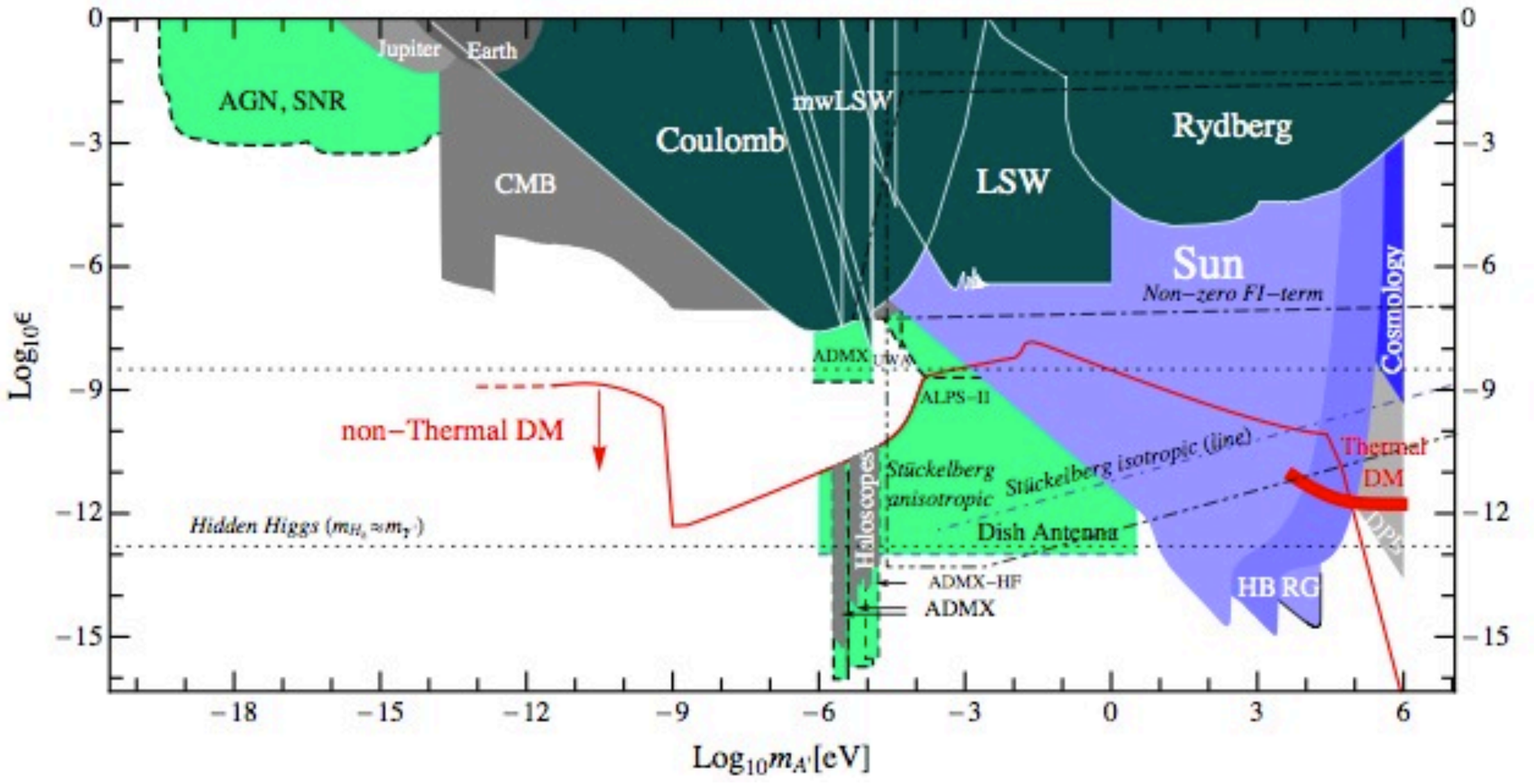
| Generic decay modes | Final states | Models tested |
|---|---|---|
| meson and lepton | $\pi l$, $Kl$, $\rho l$, $l = (e, \mu, \nu)$ | $\nu$ portal, HNL, SUSY neutralino |
| two leptons | $e^+e^-$, $\mu^+\mu^-$ | V, S and A portals, SUSY s-goldstino |
| two mesons | $\pi^+\pi^-$, $K^+K^-$ | V, S and A portals, SUSY s-goldstino |
| 3 body | $l^+l^-\nu$ | HNL, SUSY neutralino |

talk by M. Shaposhnikov
2nd SHiP collaboration meeting

SHiP can search for a wide range of signatures probing a variety of portals & models!

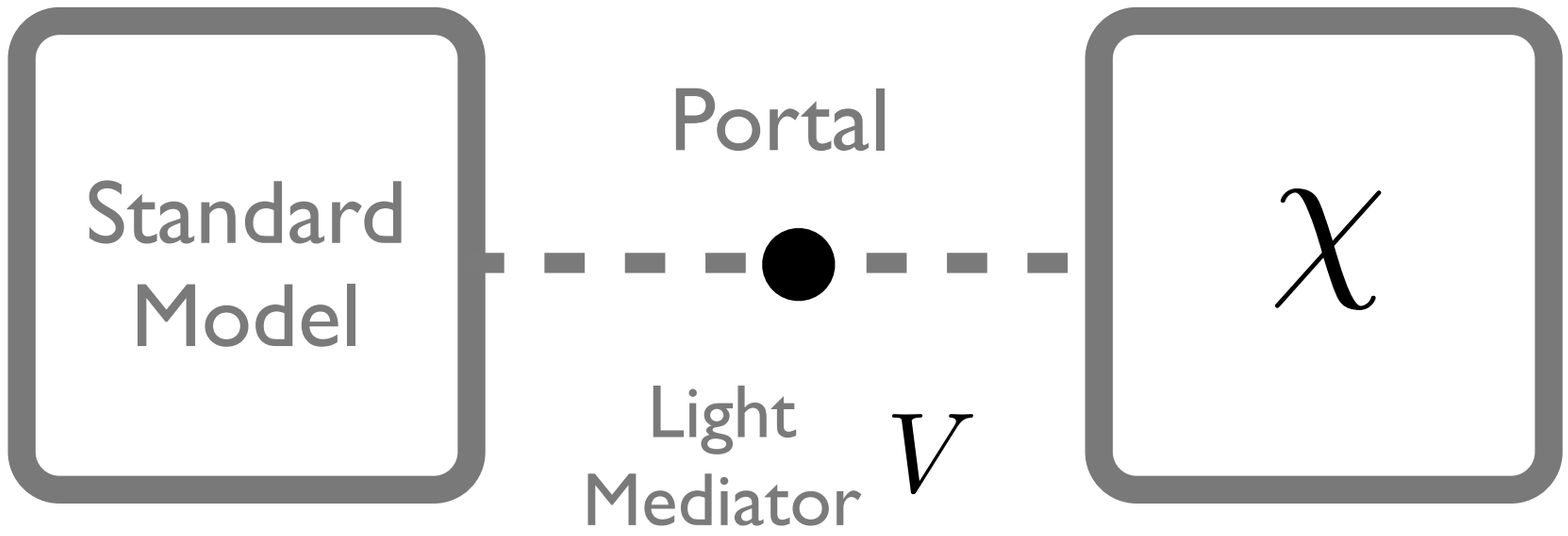
(See talk by P. Mermod)

# The low energy frontier of the vector portal

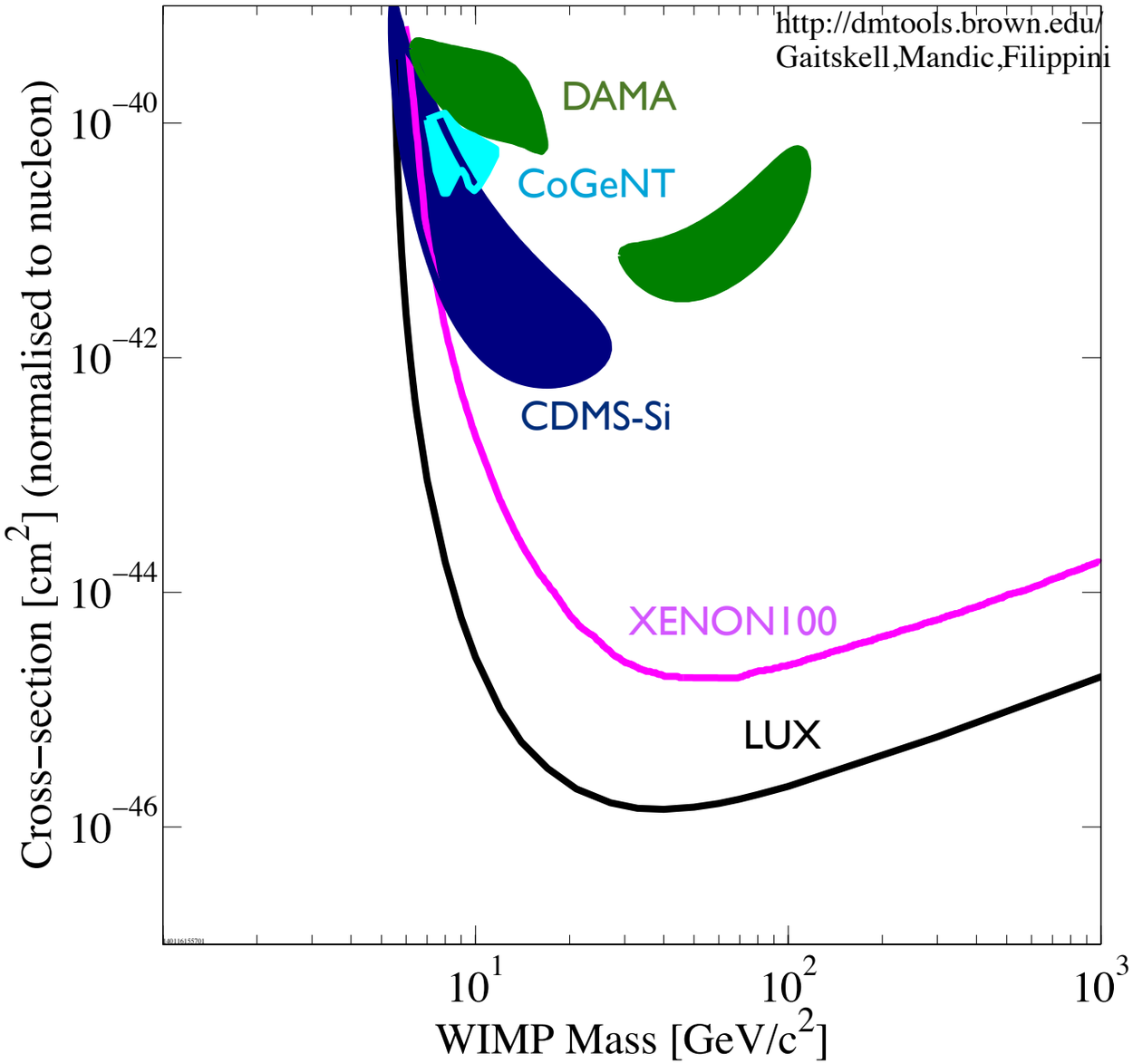



Jaeckel, Ringwald, Redondo...

# Portals to Dark Matter

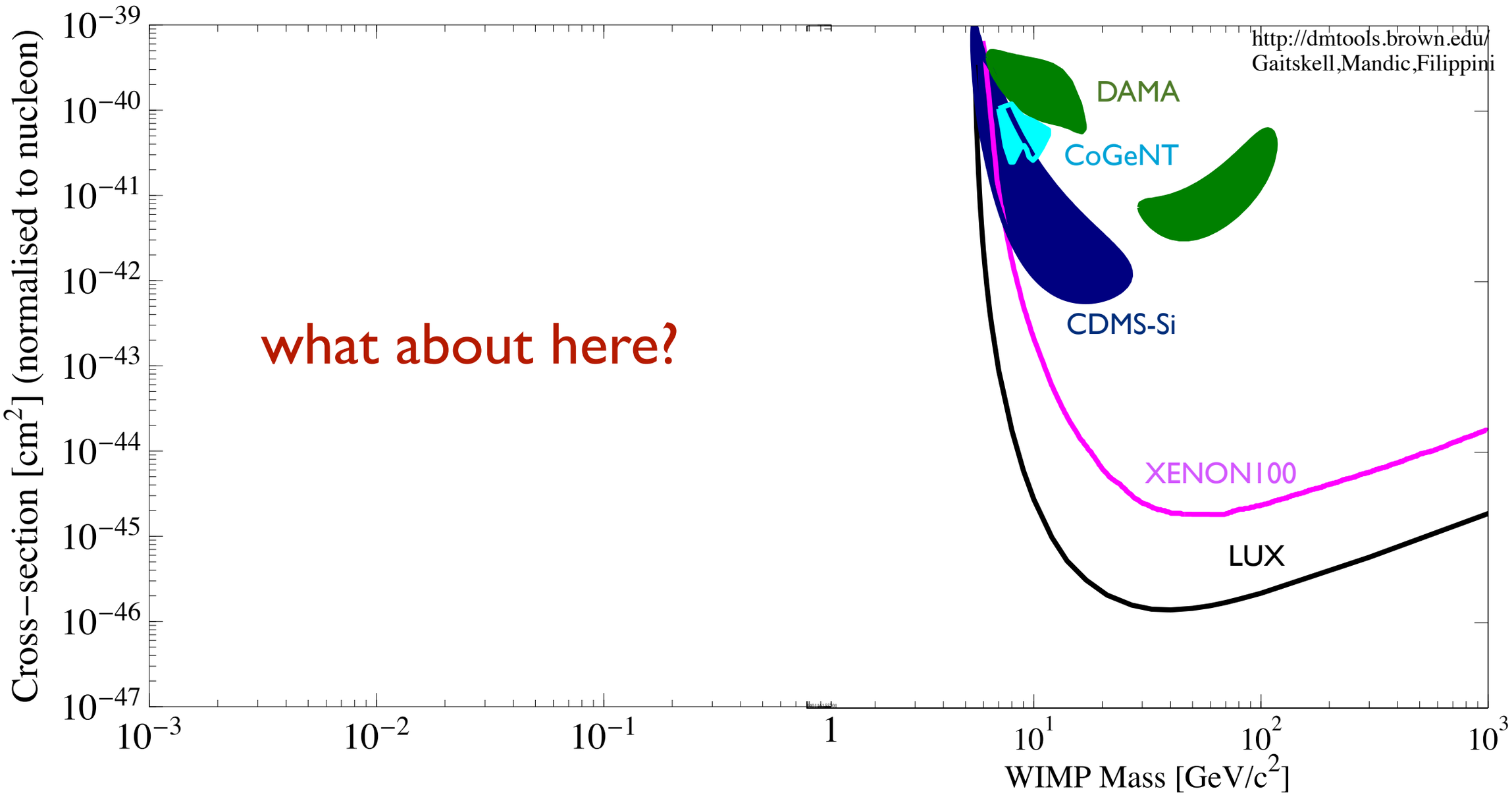


# Direct Detection



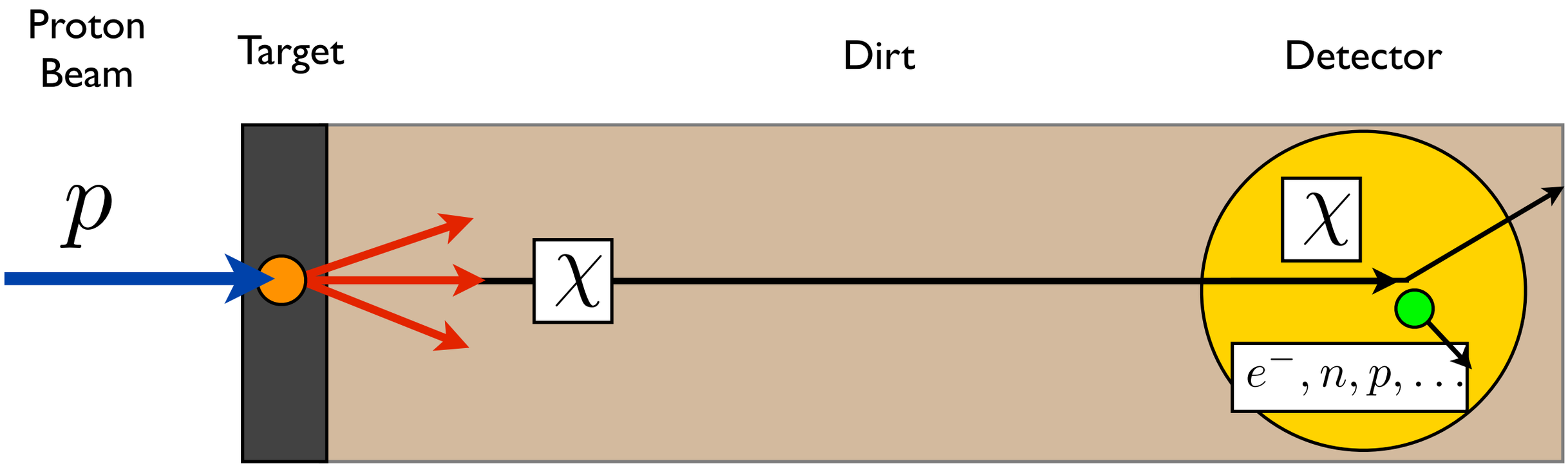

- Enormous progress over past 2 decades
- Probe DM masses above ~ GeV

# Direct Detection




- Nuclear recoil too weak - $v_{\rm DM} \sim 10^{-3}$
- Can we find a relativistic source of dark matter?

# Relativistic Dark Matter Beam!

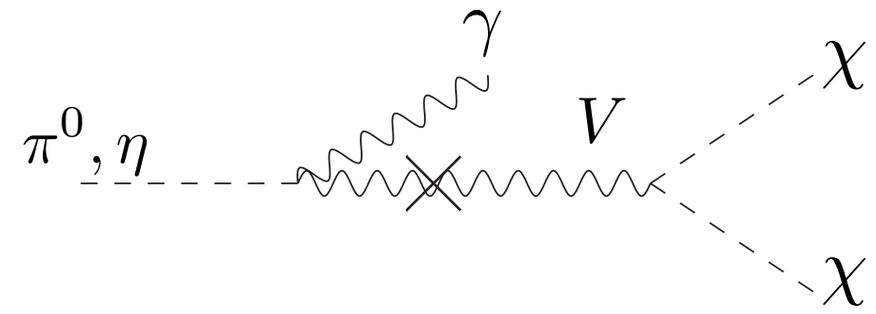



BB, Pospelov Ritz

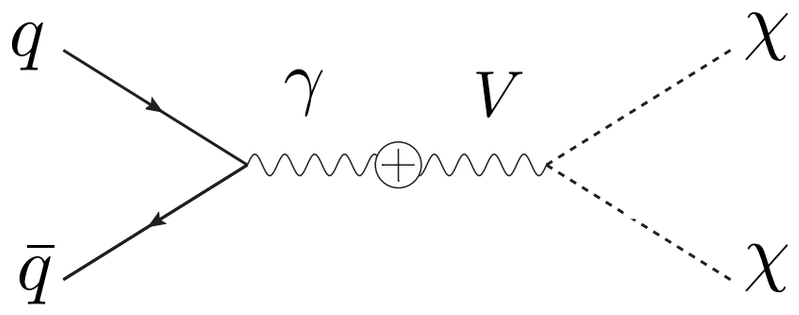
- Superior sensitivity for many models with light DM + light mediator
- Provides a strong motivation for intense proton sources, such as SPS at CERN

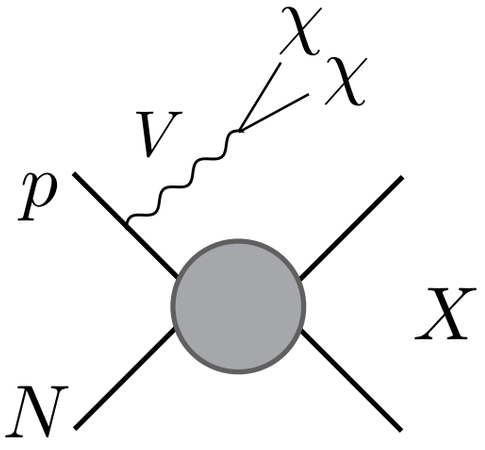
# Production of the Dark Matter beam

Hadron decays

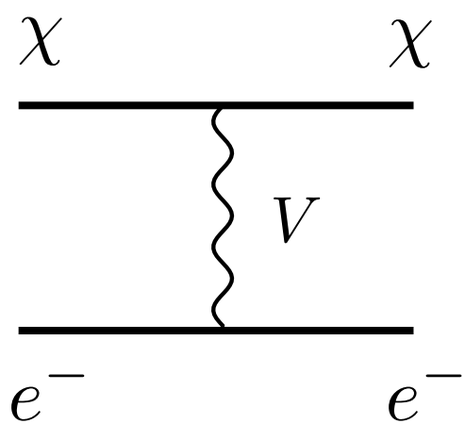



Direct production

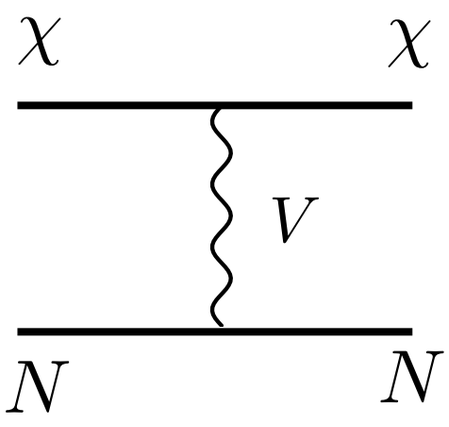


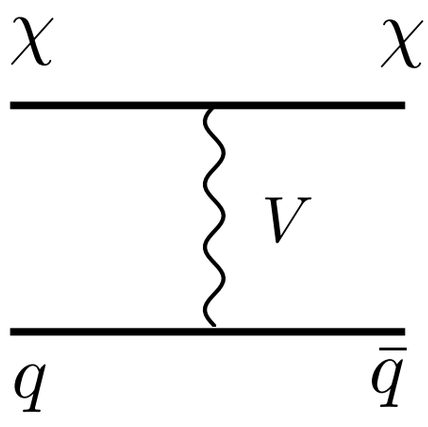

# Detection via scattering - anomalous neutral currents




$\chi - e^-$ elastic




$\chi -$ nucleon elastic




deep inelastic

# Vector portal DM ("dark force")

[Pospelov, Ritz, Voloshin],

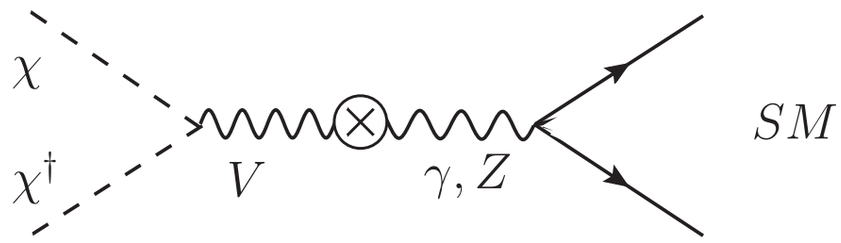
$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4}(V_{\mu\nu})^2 + + \frac{1}{2} m_V^2 (V_\mu)^2 - \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu} + \dots$$

$$D_\mu = \partial_\mu - i g_D V_\mu$$

- Dark photon mediates interaction between DM and SM

- 4 new parameters: $m_\chi, m_V, \kappa, \alpha'$ $\qquad (V = A',\ \kappa = \epsilon,\ \alpha' = \alpha_D)$

- Scalar DM annihilation is p-wave, CMB ok



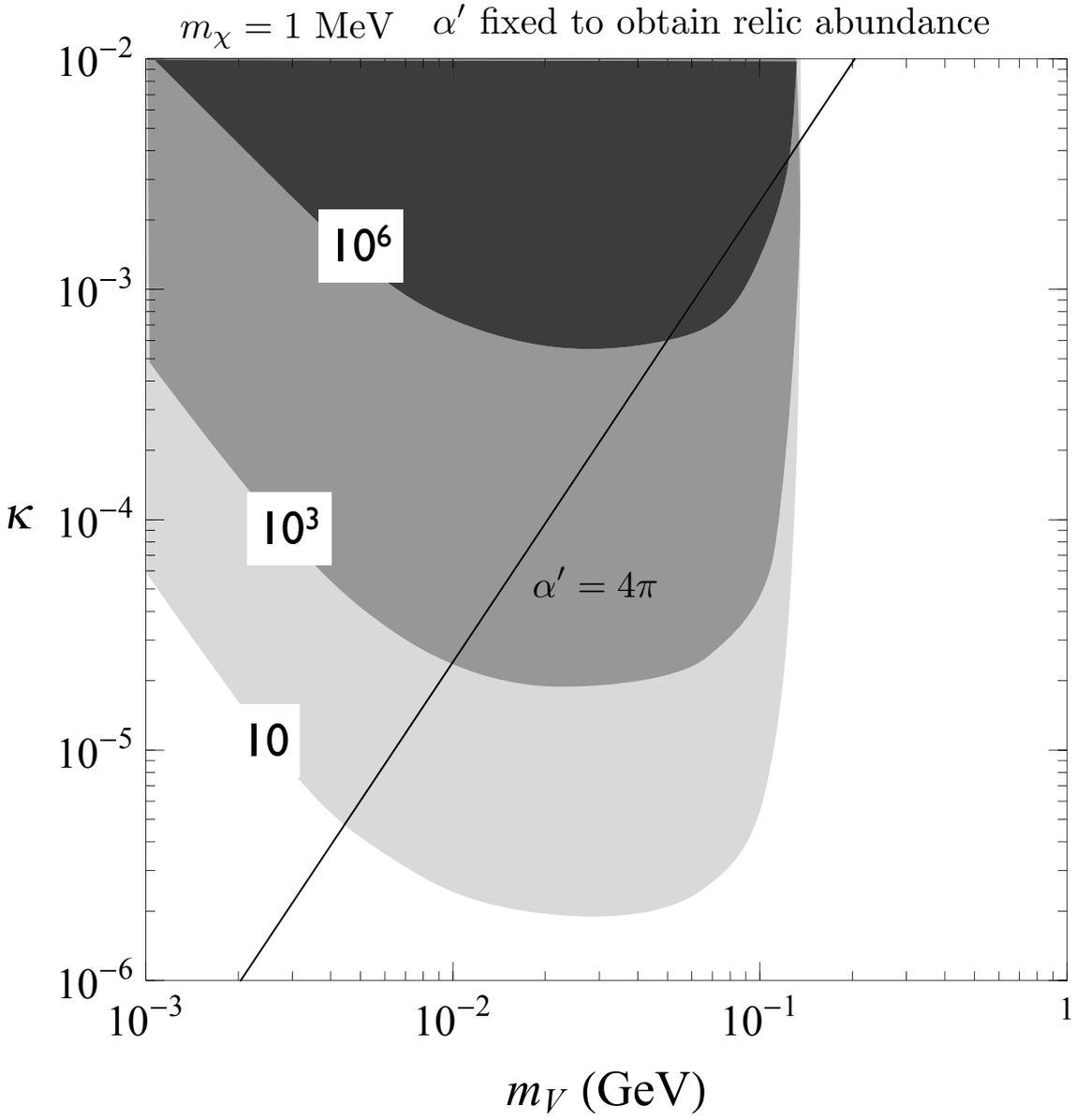
# LSND

Production: $\pi^0 \to \gamma V \to \gamma \chi \bar{\chi}$

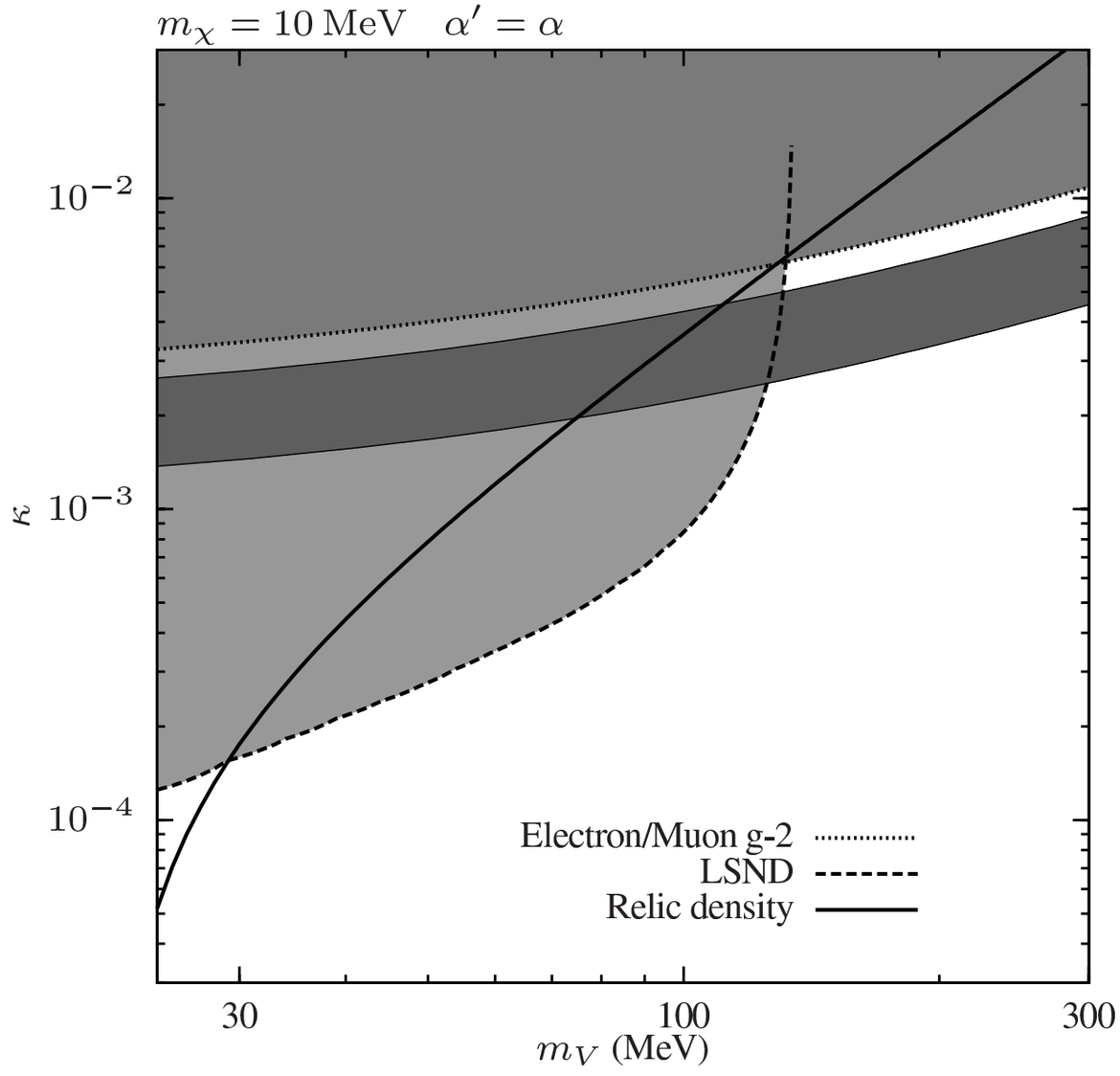
Sensitivity to $\chi e \to \chi e$

[Auerbach et al. (LSND Collaboration), '01]

- LAMPF, 800 MeV protons, ~ $10^{23}$ POT
- water / high Z target
- detector: 30m off axis from target, cylindrical, 170 tons mineral oil




BB, Pospelov, Ritz



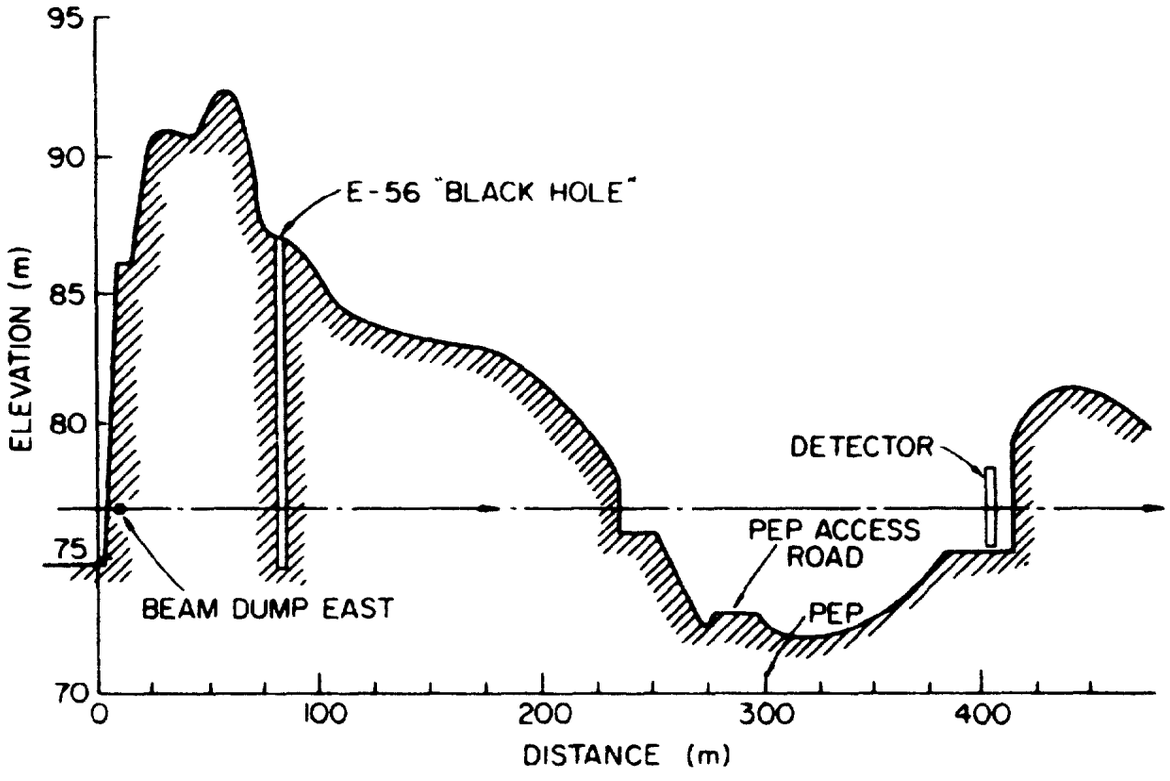

deNiverville, Pospelov, Ritz

# SLAC E137

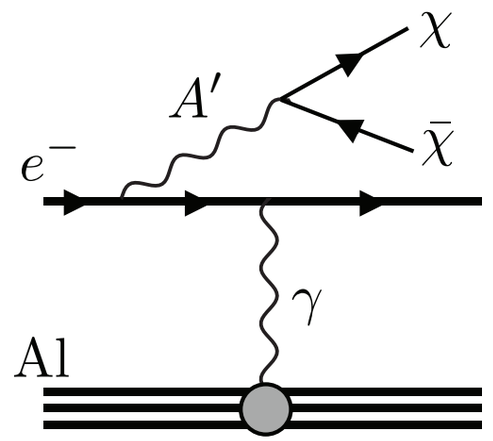
BB, Essig, Surujon

[Bjorken et al., (E137 Collaboration) '88]

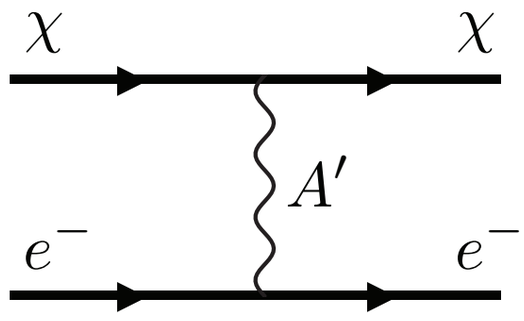
- 20 GeV electron beam; 30 C dumped;
- Aluminum target
- Shower calorimeter detector, 400m from dump



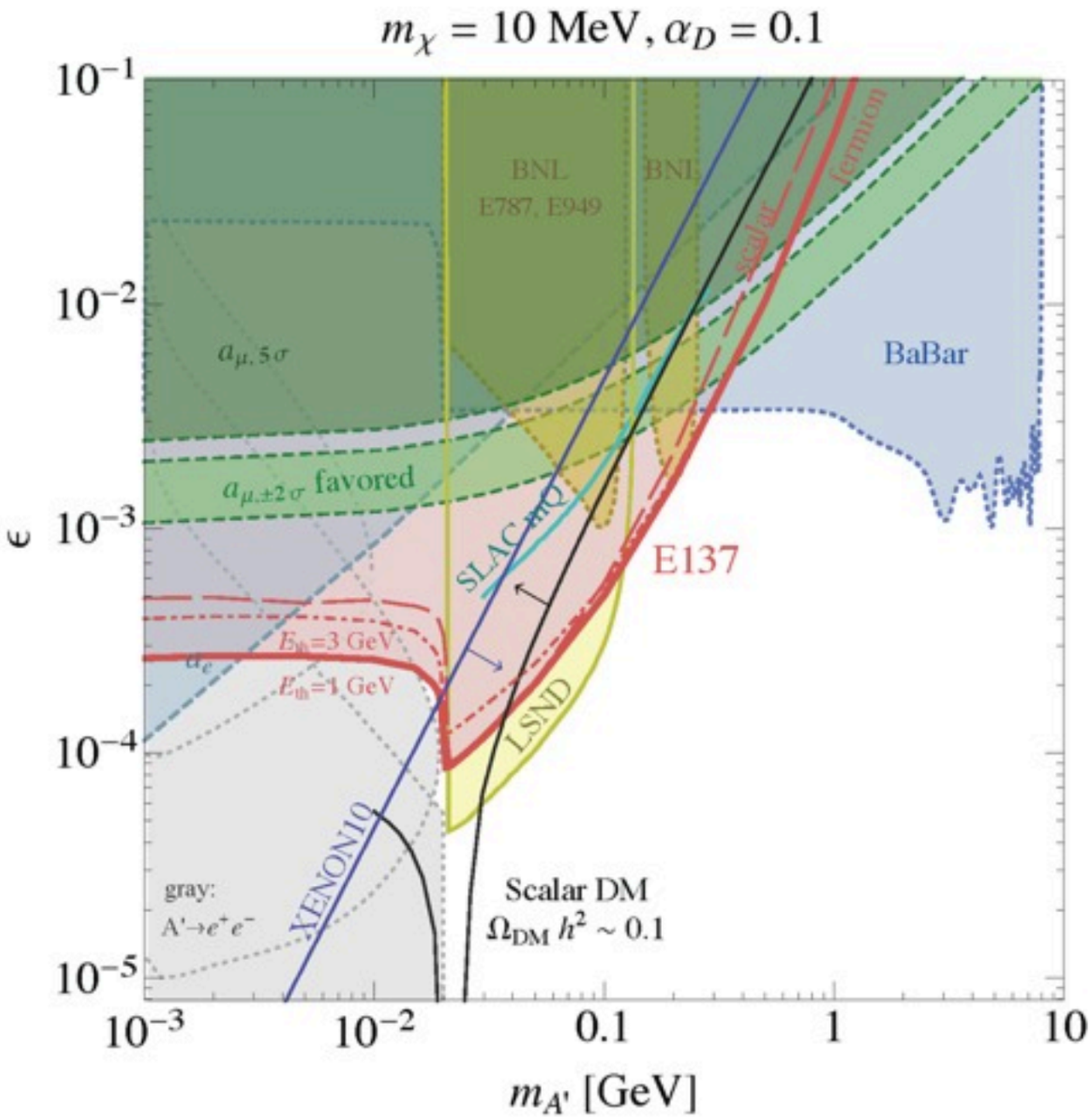

Production

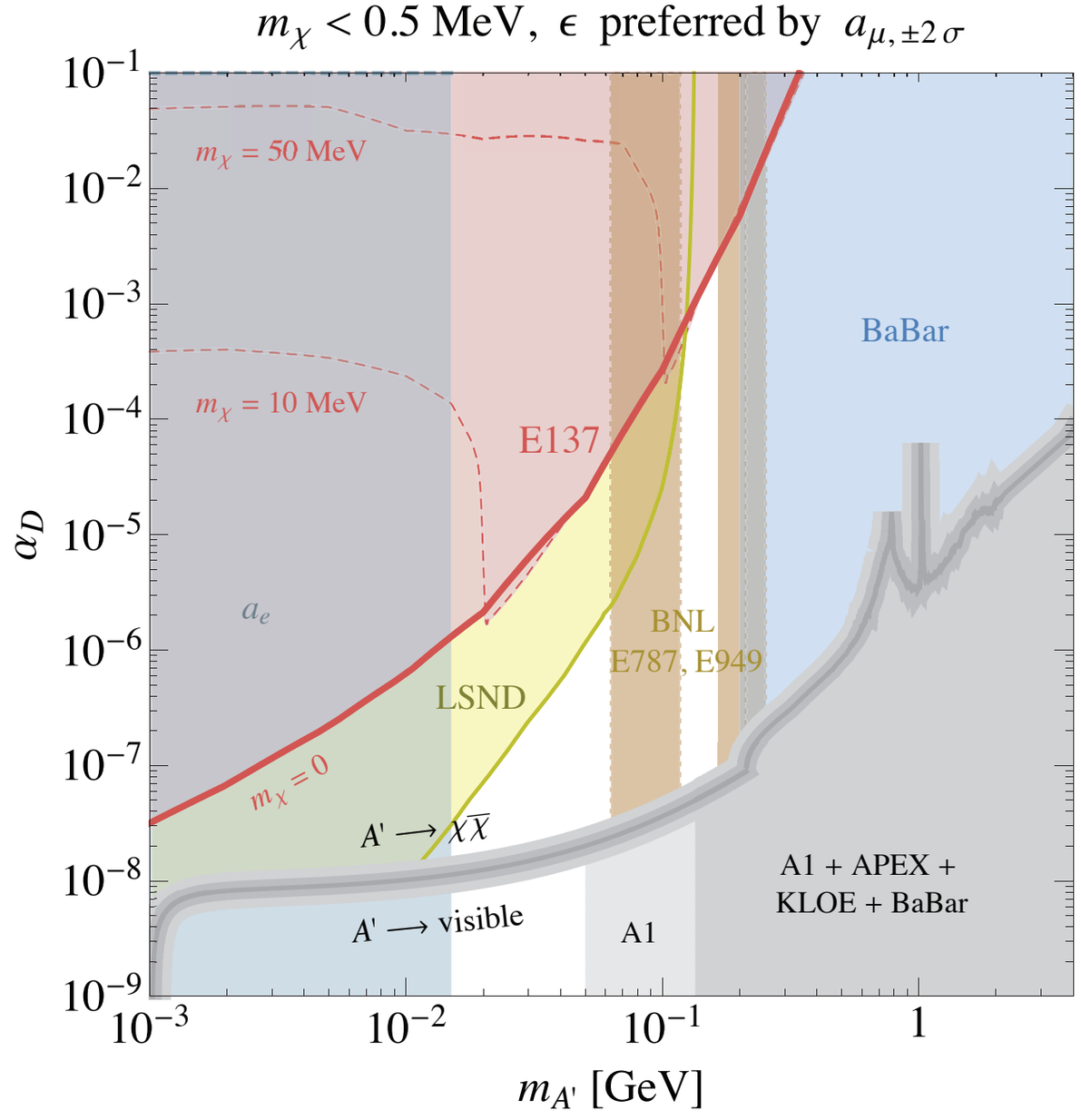



Scattering




# Current constraints on vector portal DM




BB, Essig, Surujon

# Leptophobic DM

BB, deNiverville, McKeen, Pospelov, Ritz
Dobrescu, Frugiuele

- Dark matter couples dominantly to quarks

- Focus on model based on local $U(1)_B$ baryon number symmetry

$$\mathcal{L} = i\bar{\chi}\gamma^\mu D_\mu \chi - m_\chi \bar{\chi}\chi - \frac{1}{4}(V_B^{\mu\nu})^2 + \frac{1}{2}m_V^2 (V_B^\mu)^2 + \frac{g_B}{3} V_B^\mu \sum_i \bar{q}_i \gamma_\mu q_i + \dots$$

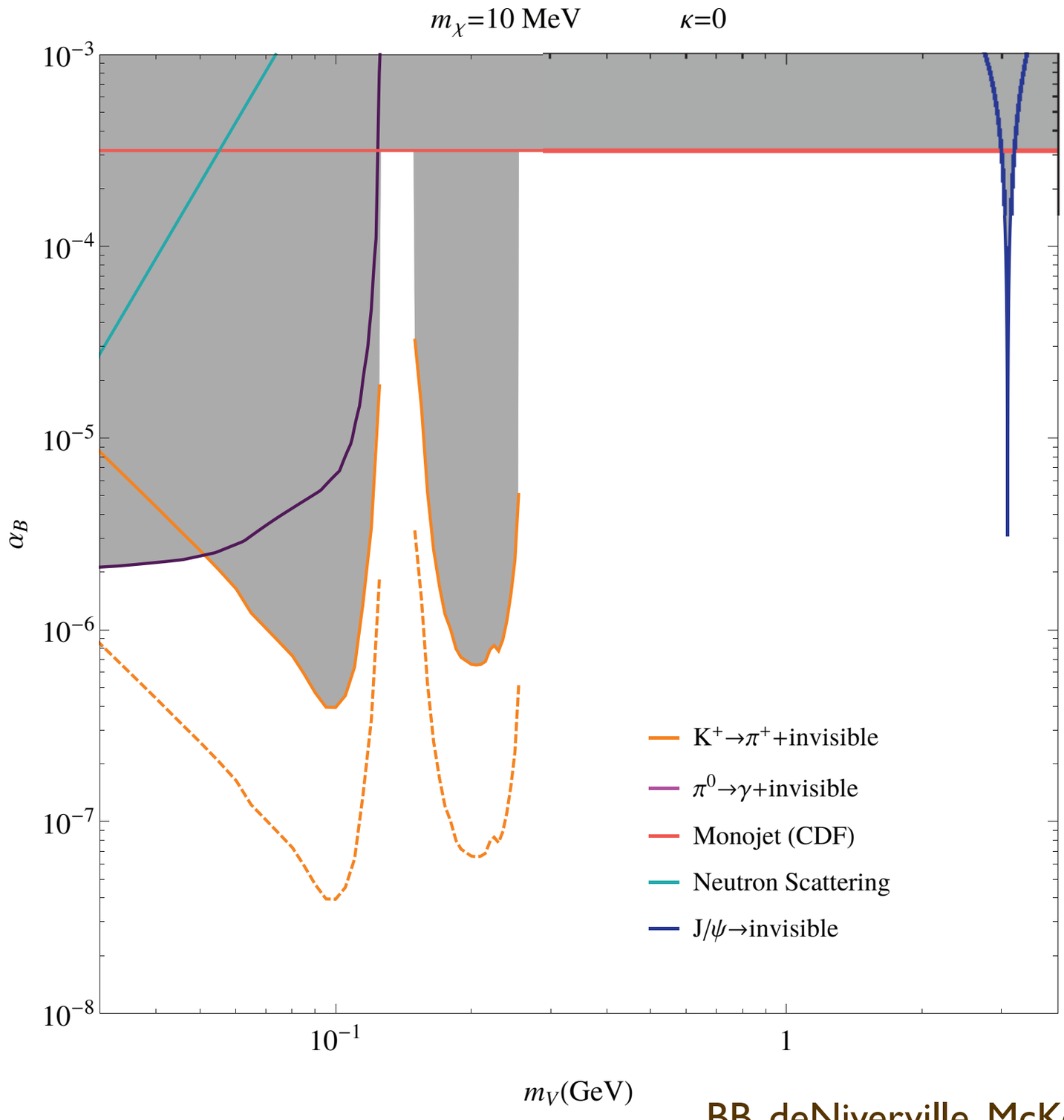
$$D^\mu = \partial^\mu - i g_B q_B V_B^\mu$$

- 4 new parameters: $m_\chi, m_V, \alpha_B, q_B$

- $U(1)_B$ is "safe" - preserves approximate symmetries of SM (CP, P, flavor)

- Gauge anomalies can be cancelled by new states at the weak scale

# Much weaker constraints compared to vector portal DM!




BB, deNiverville, McKeen, Pospelov, Ritz

# MiniBooNE dedicated beam dump run to search for dark matter

[Dharmapalan et al. ,(MiniBooNE Collaboration), arXiv:1211.2258]

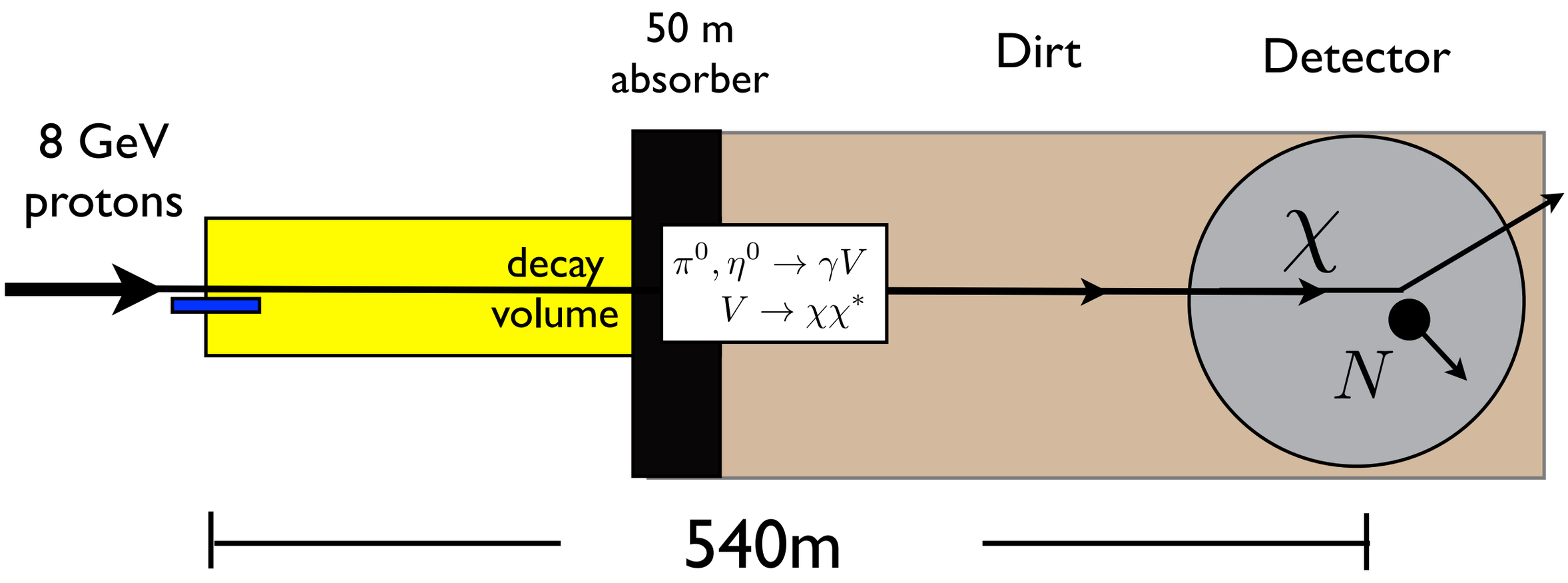
- Basic idea: direct protons onto beam dump to reduce neutrino flux
- Proposal to the FNAL PAC
- Run approved fall 2013; just finished this September
- 2 E 20 POT collected
- Analysis underway - results this year!

# Beating down the neutrino background

The signature of dark matter is a neutral current scattering event

Very similar to neutrino induced neutral current event!

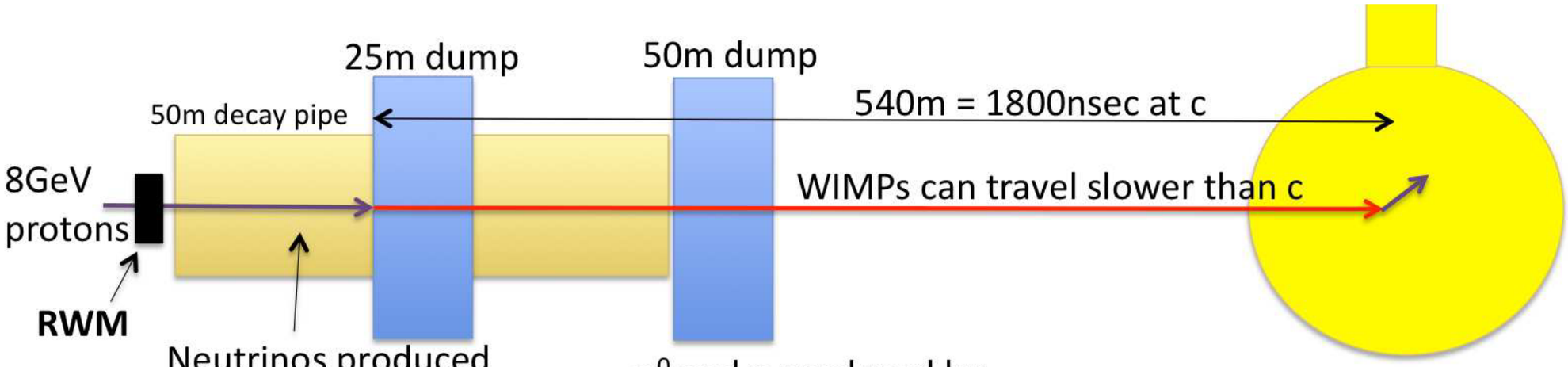
Focus protons onto the beam dump - charged pions absorbed or stopped!



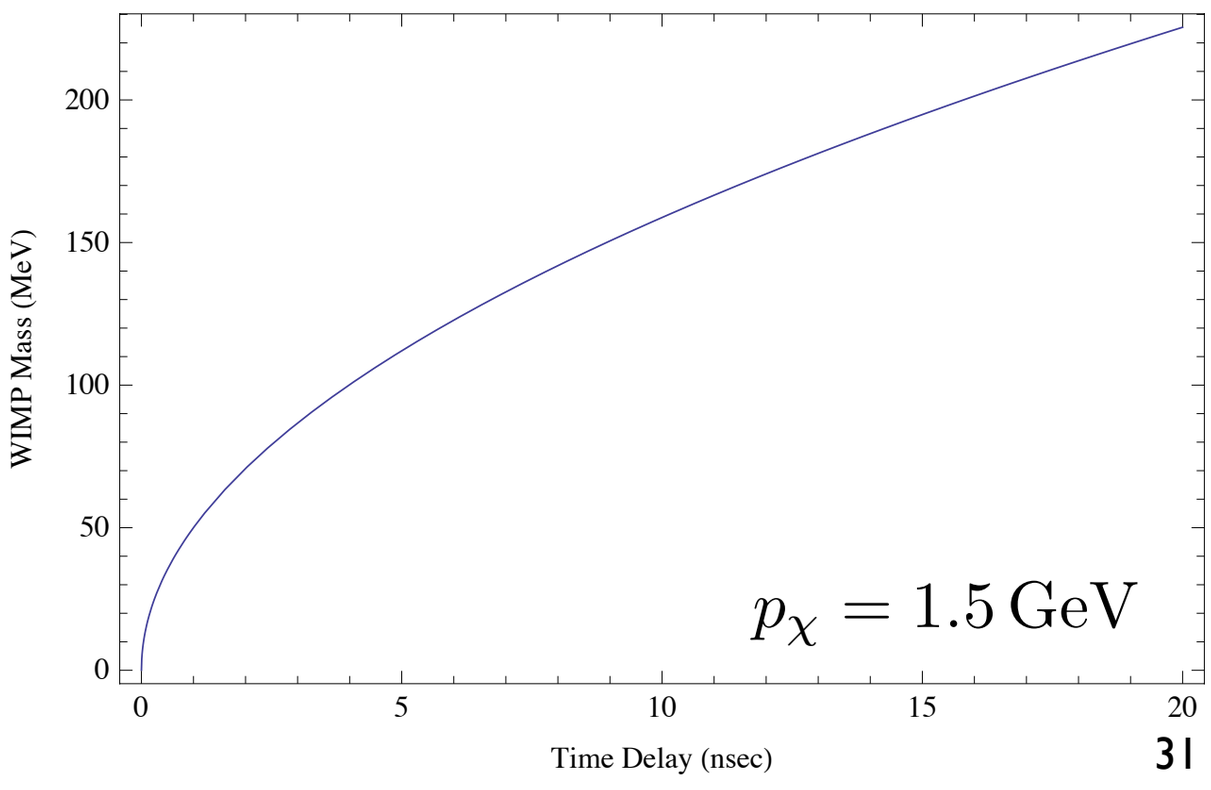

Neutrino background reduced by factor of ~ 50!

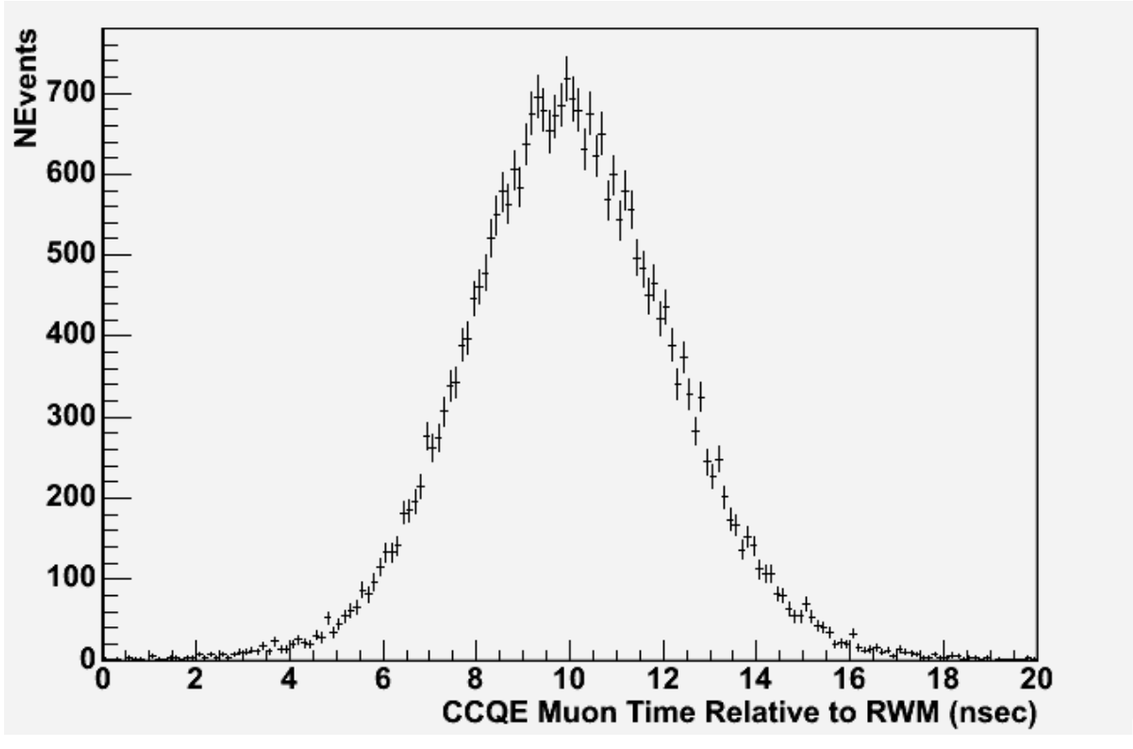
# Timing

Dark matter is heavier than neutrinos - arrives at the detector later!

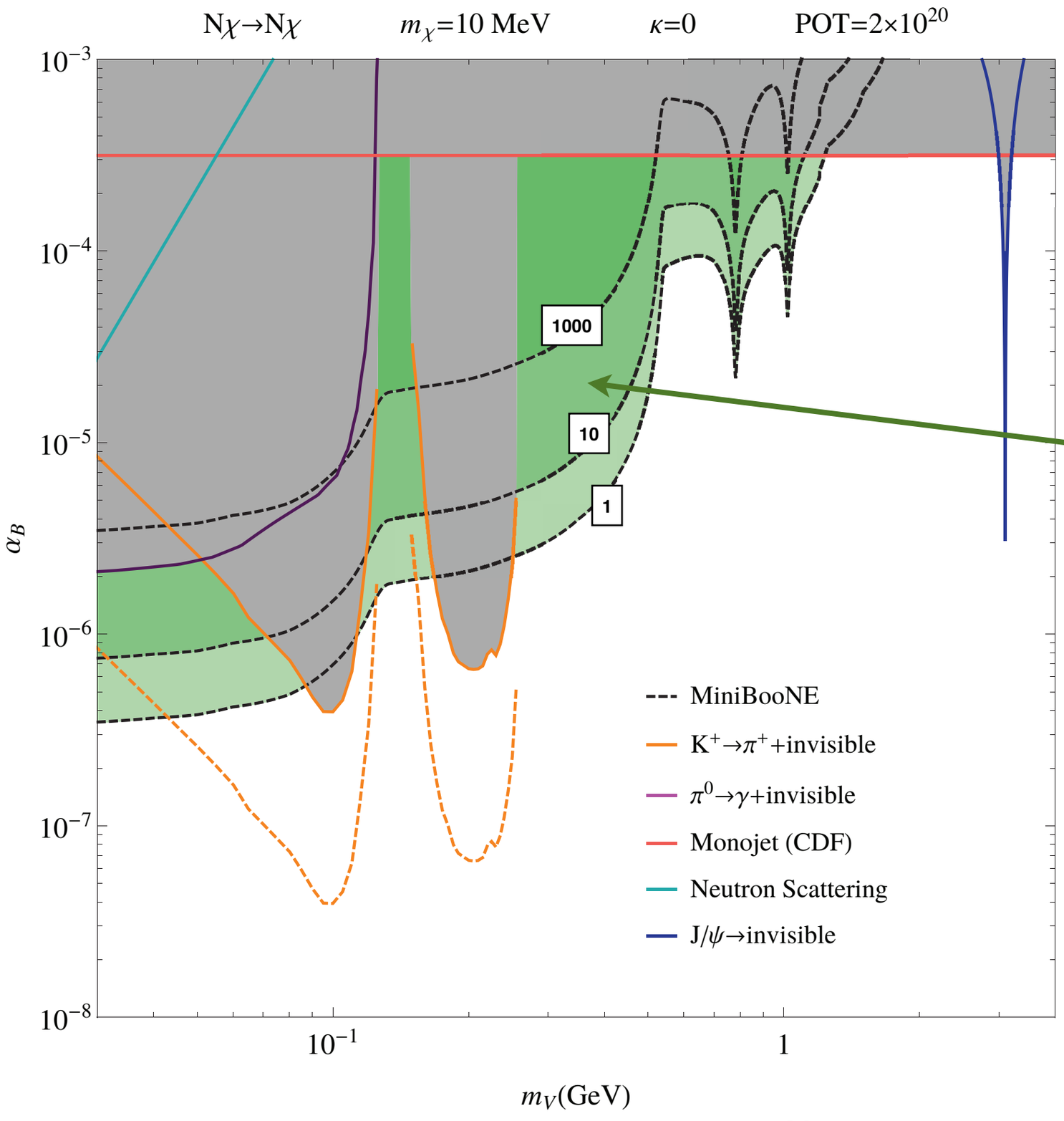



5-10 ns timing resolution



# MiniBooNE sensitivity to leptophobic DM




MiniBooNE signal

Unique sensitivity over much of the parameter space!

# Many promising proposals to probe Sub-GeV Dark Matter

- Direct detection via scattering with electrons Essig, Mardon, Volansky

- Electron Beam fixed target - scattering experiments
  - BDX (Beam Dump eXperiment) Izaguirre, Krnjaic, Schuster, Toro

- Fixed target - missing momentum experiments
  - SPS Proposal P348 http://p-348.web.cern.ch/

    Andreas et al. 1312.3309

(See also
Kahn, Thaler
Izaguirre, Krnjaic, Schuster, Toro)

- Neutrino factories, e.g., DAEdULUS Kahn et al.

# Outlook

- Strong empirical hints for new physics (Dark Matter, Neutrino mass, Baryon Asymmetry), but we do not know the scale associated with their dynamics - can be light!

- We have a variety of experimental tools at our disposal to search for such new lights states - high intensity, high precision, and high energy experiments. We must take full advantage of these resources.

- Portals allow a systematic approach to the study of such states.

- We don't know which principle is the right one in guiding us in our search for new physics. We must look everywhere we can - at, above and below the weak scale. Any discovery will be revolutionary!