Spin-1 Thermal Targets for Dark Matter Searches at LDMX

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X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

Outline

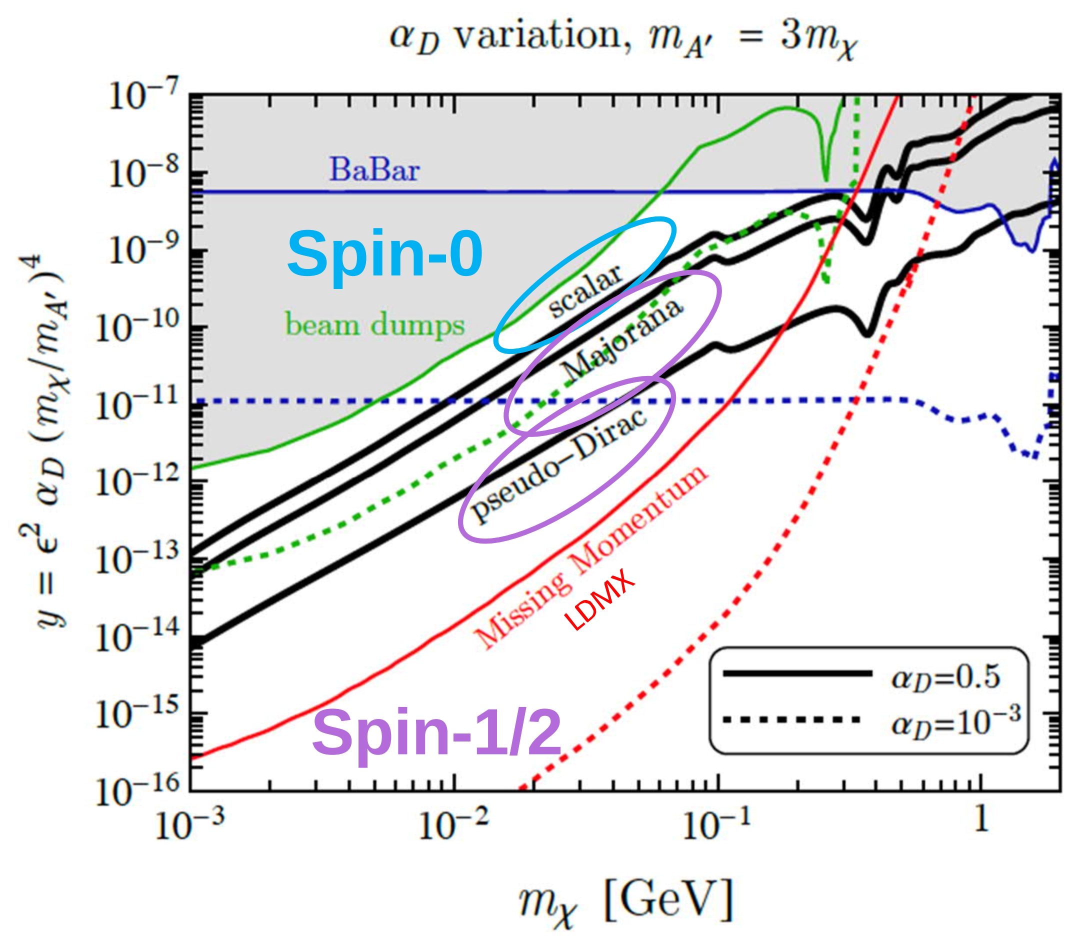
- Introduction
    - current landscape of sub-GeV DM to be probed at LDMX
- Goal
    - identify new spin-1 thermal targets for DM searches at LDMX
- Calculations/Methods
    - spin-1 DM model
    - relic density
    - other limits/projections
- Numerical Results
- Conclusions

Sub-GeV
Dark Matter

- Fixed target experiments can probe sub-GeV DM

- Future fixed target experiments such as **LDMX** will reach new sensitivities in the sub-GeV mass range.

- How about **spin-1** DM?



arXiv:1807.0170

The Goal

Identify new spin-1 thermal sub-GeV DM targets for searches at LDMX to broaden existing studies.

Spin-1 Dark Matter

with a Dark Photon Mediator

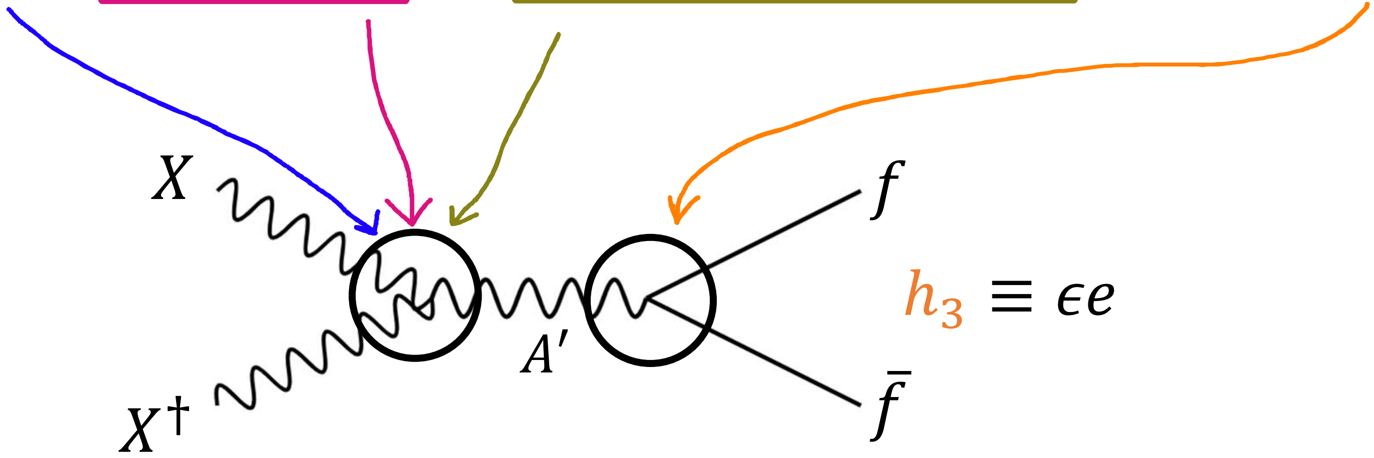
$$-\mathcal{L} \supset \Big(\underbrace{i b_5 X^\dagger_\nu \partial_\mu X^\nu A'^\mu}_{} + \underbrace{b_6 X^\dagger_\mu \partial^\mu X_\nu A'^\nu}_{} + \underbrace{b_7 \epsilon_{\mu\nu\rho\sigma} \left(X^{\dagger\mu} \partial^\nu X^\rho\right) A'^\sigma}_{} + h.c.\Big) + \underbrace{h_3 A'_\mu \bar{f} \gamma^\mu f}_{}$$

b_5: real

b_6: complex

b_7: complex

h_3: real



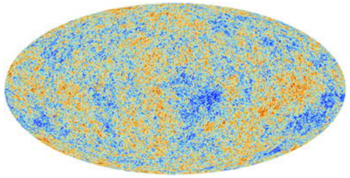
$h_3 \equiv \epsilon e$

f: SM leptons and quarks (excluding neutrinos)

If $2m_X < m_A$, s-channel dominates DM annihilations.

Relic Target Calculation

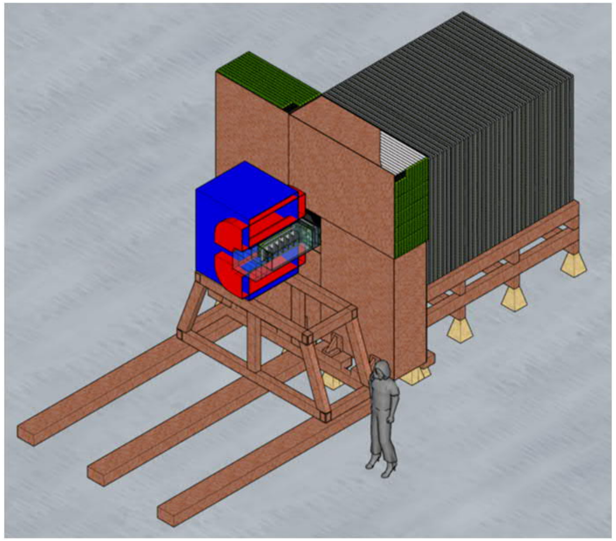
- DM relic abundance consistent with Planck
  - $\Omega h^2 \approx 0.12$



- Assume DM is produced through freeze-out.
- $3\mathrm{m}_{\mathrm{X}} = \mathrm{m}_{\mathrm{A}'}$
- DM relic density dominantly set by on-shell s-channel A′ exchange:
  - $\mathrm{XX}^{\dagger} \rightarrow \mathrm{A}' \rightarrow \mathrm{f}\bar{\mathrm{f}}$

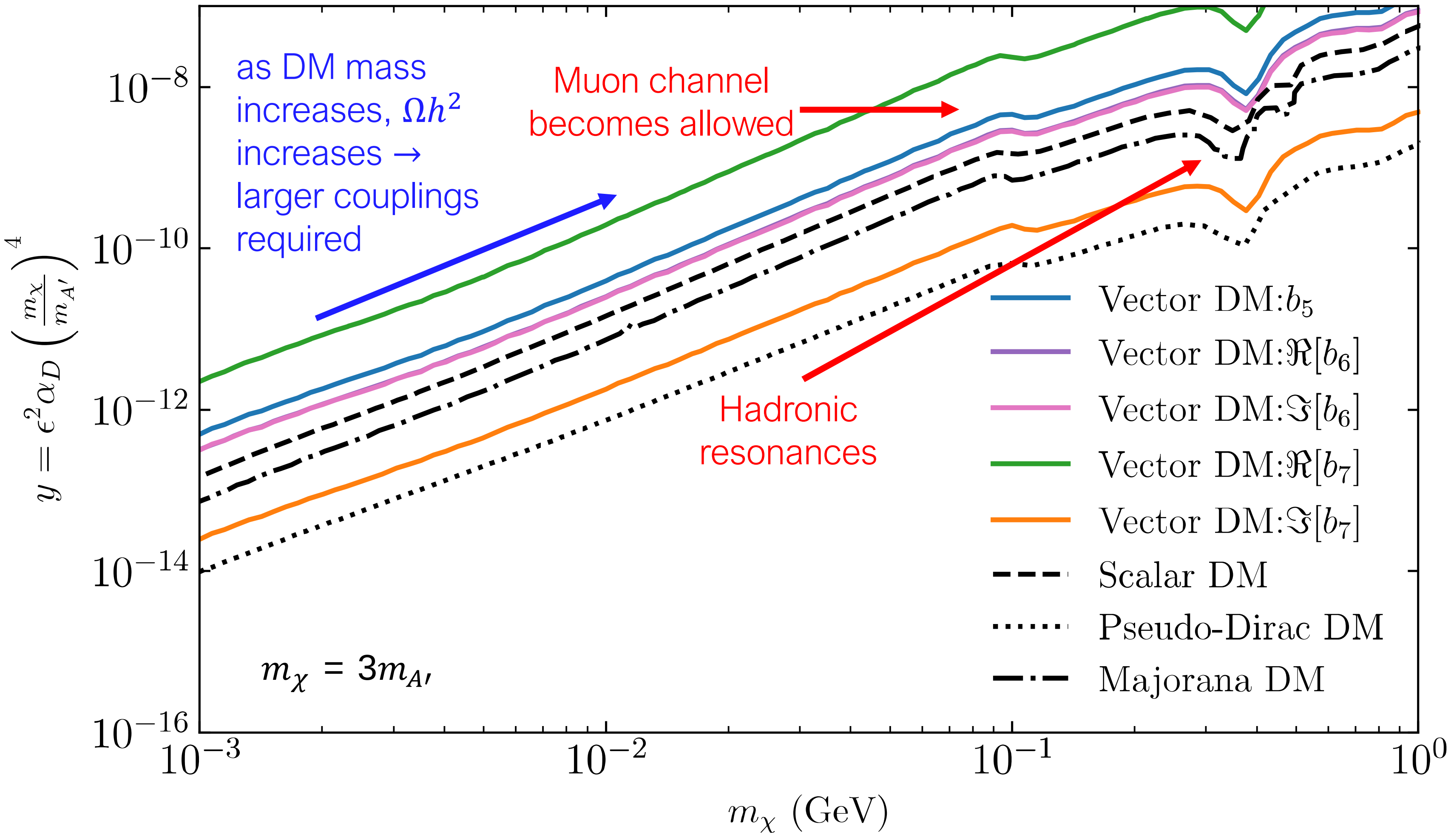
Experimental Reach

- Place exclusion/projection bounds on parameter space.
  - current + future experiments
  - cosmological + theoretical bounds



LDMX

Relic Targets of DM Models



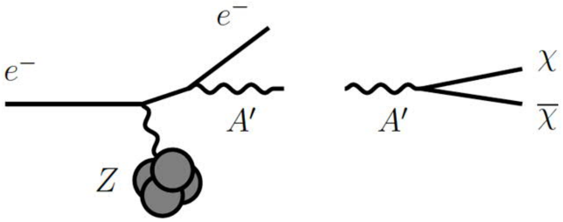
as DM mass increases, Ωh^2 increases → larger couplings required

Muon channel becomes allowed

Hadronic resonances

Limits/Projections

Electron Bremsstrahlung + (In)Visible Decay



LDMX

- Missing Energy/Momentum
- arXiv:1808.05219

SLAC E137

arXiv:1406.2698

NA64

arXiv:1906.00176

Proton Beam Dumps with Downstream DM Detector

LSND

arXiv:1107.4580

Mini-Boone

arXiv:1702.02688

BaBar

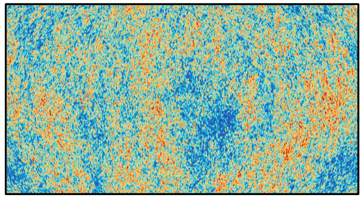
- $e^+e^- \rightarrow \gamma A', A' \rightarrow XX$

arXiv:1702.03327

Direct Detection

- $Xe^- \rightarrow Xe^-$
- SENSEI, XENON, CRESST II
- In progress!

Energy Injection



Limits/Projections:

Energy Injection in the early universe

Injection of EM particles into the universe during its early history leads to changes in CMB anisotropies and the IGM temperature.

CMB

$$P_{ann} \equiv f(z)\frac{<\sigma v>_{\chi\chi\rightarrow f\bar{f}}}{m_\chi}$$

$$P_{ann} \lessapprox 3.2 \times 10^{-28} cm^3 s^{-1} GeV^{-1}$$

(Planck 2018)

(s-wave DM)

- CMB anisotropies measurements by Planck constrain the annihilation parameter, P_{ann}
- Limits are placed on DM annihilation under the assumption that the power deposited is directly proportional to that injected at the same energy (with efficiency $f(z)$)

arXiv:1506.03811

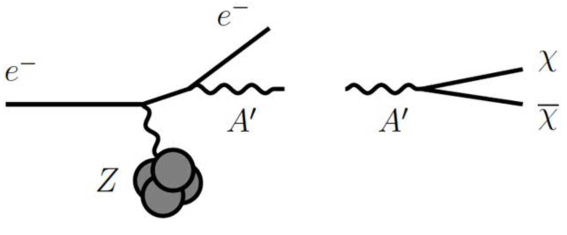
IGM

- Require that energy injected into IGM does not overheat it at late times
- Measurements of IGM temperature from Lyman-α spectra constrain DM annihilation
- p-wave DM

10.1103/PhysRevD.104.043514

Limits/Projections

Electron Bremsstrahlung + (In)Visible Decay



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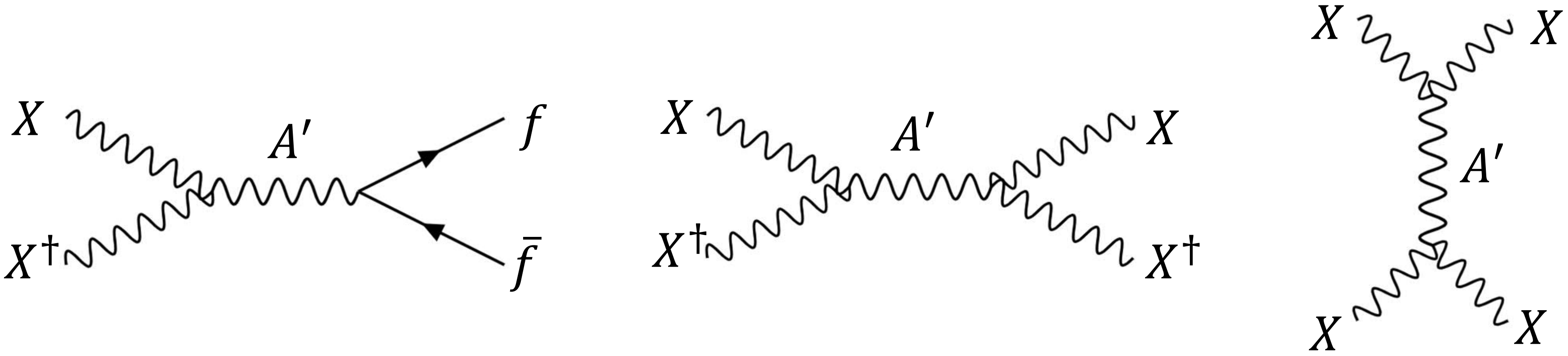
Energy Injection

Unitarity

Limits/Projections: Unitarity

If the scattering amplitude of our theory is too large at tree level, loop corrections are needed, thus the theory is not perturbative.

$$|Re(\mathcal{M})| \leq 1/2$$



This leads to an upper bound on the couplings (b_5, b_6, b_7, h_3).

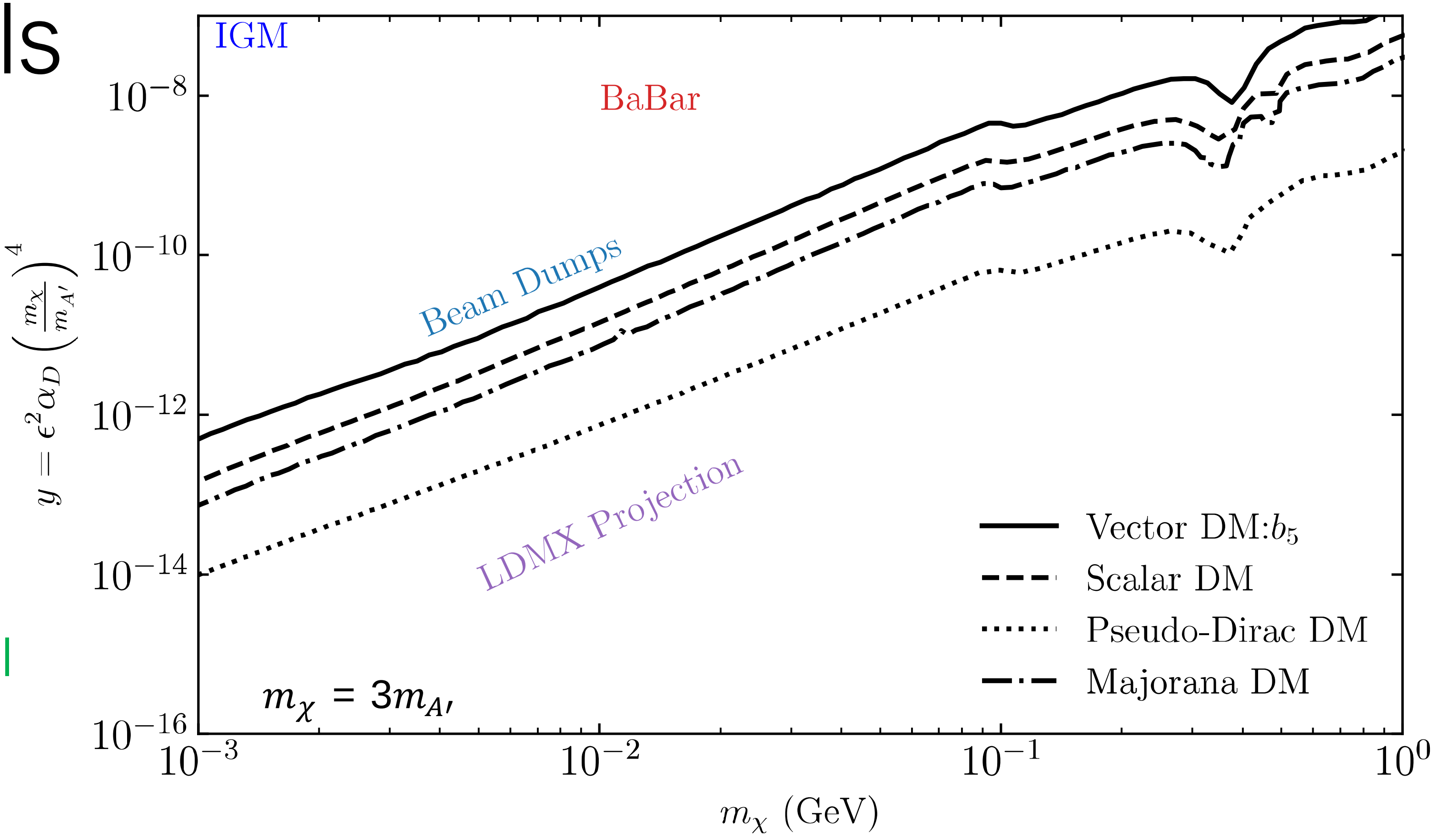
Experimental Limits/Projections on DM Models

LDMX projection

- 10% radiation length tungsten target
- 8 GeV electron beam
- 10^{16} EOT

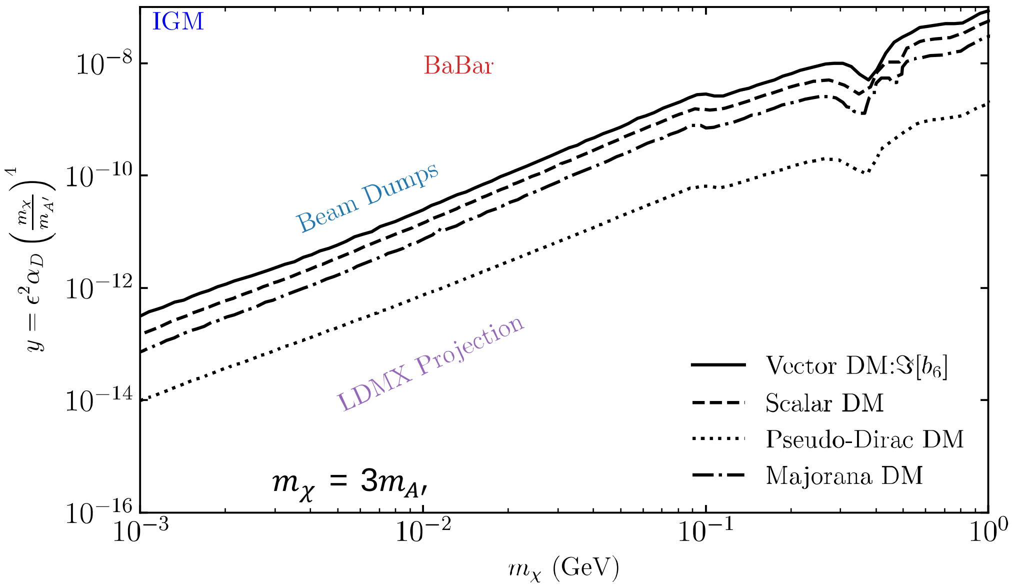
Vector DM is the first model to be probed by LDMX!

only b_5 non-zero

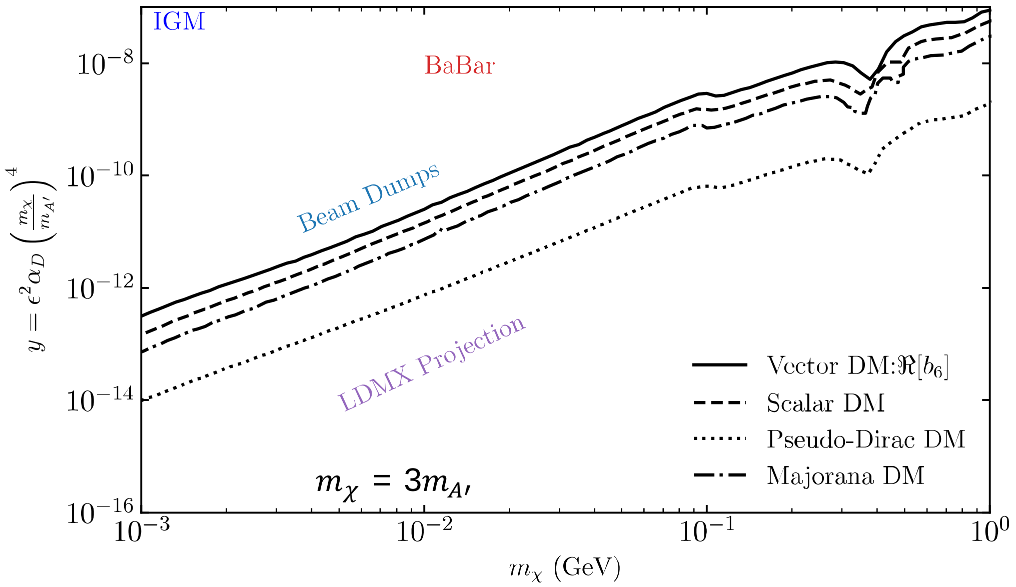


Experimental Limits/Projections on DM Models

only $\Im[b_6]$ non-zero

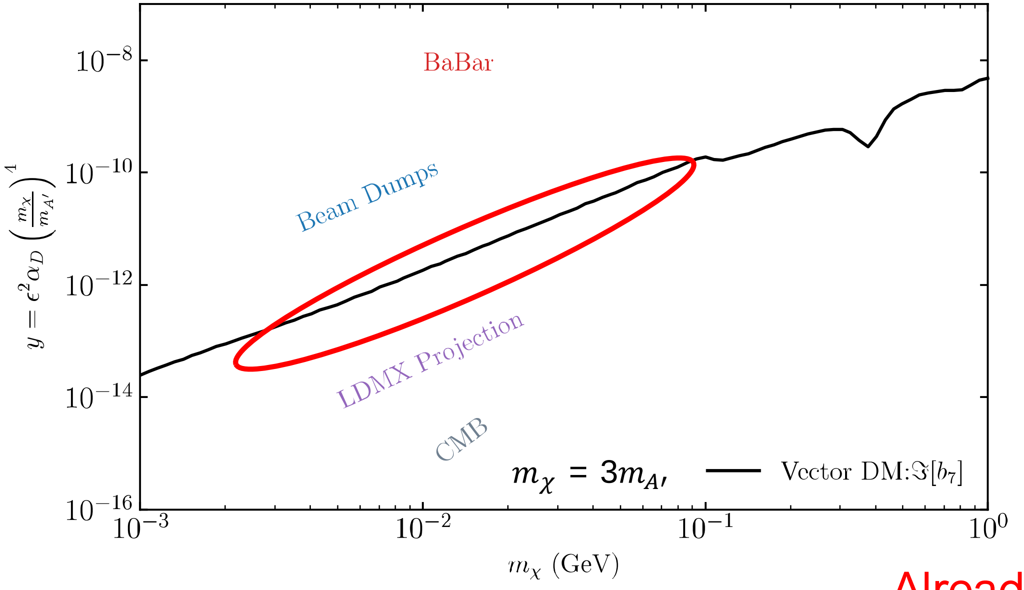


only $\Re[b_6]$ non-zero

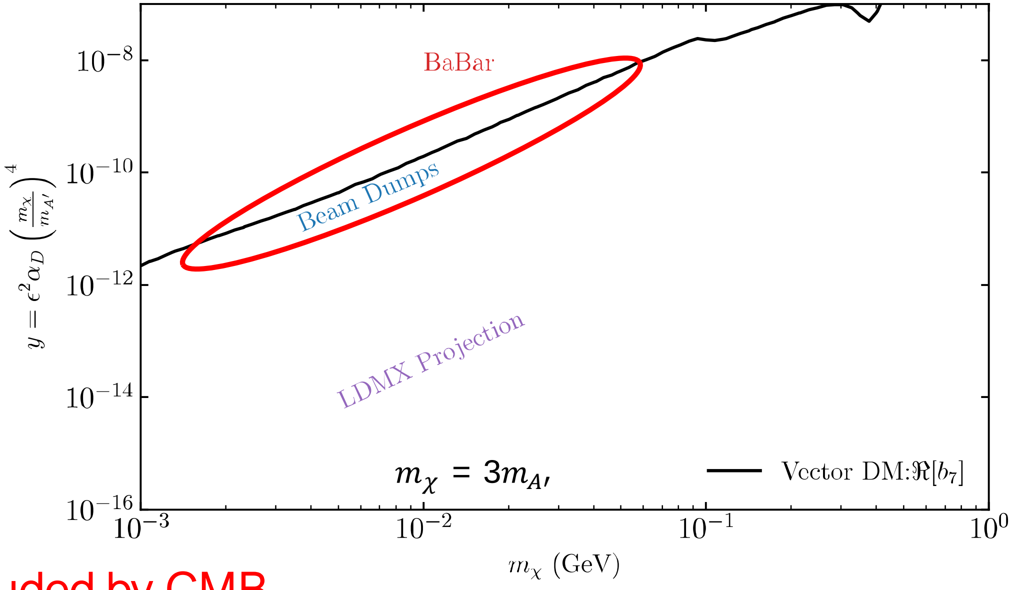


First models to be probed by LDMX!

Experimental Limits/Projections on DM Models



only $\Im[b_7]$ non-zero



only $\Re[b_7]$ non-zero

Already Excluded by CMB
and current beam dumps!

Summary and Future Work

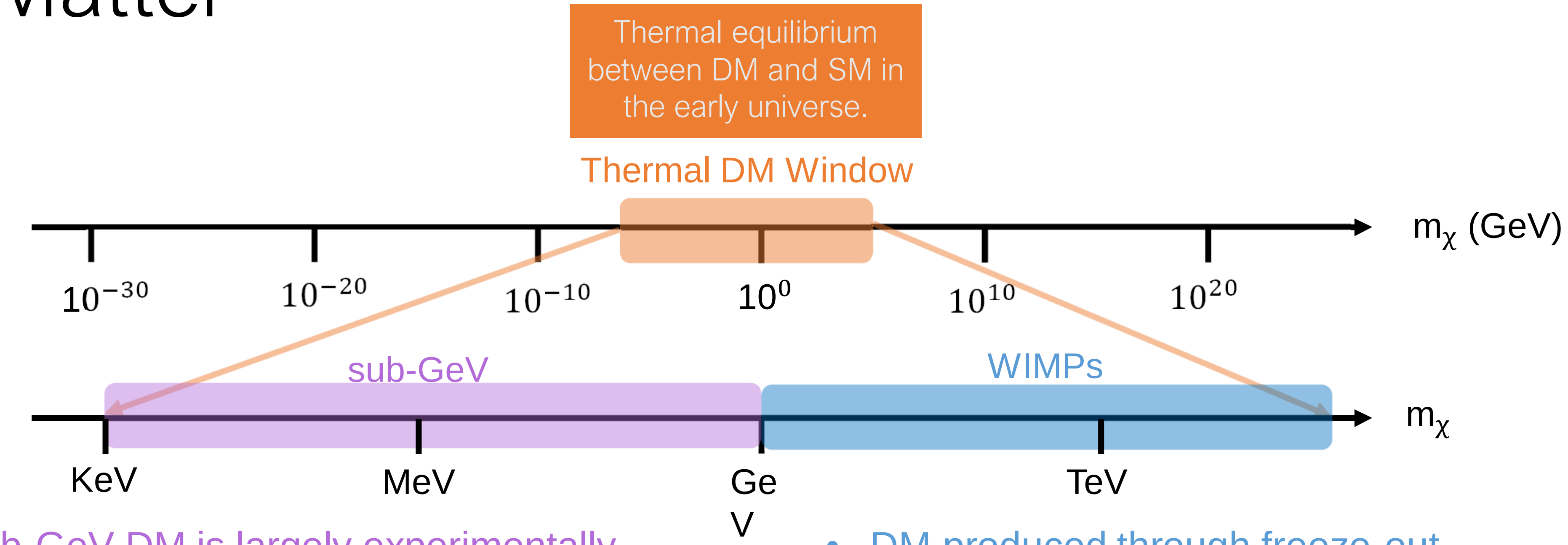
- **Extending** the current landscape of **sub-GeV DM models** considered in the context LDMX and more.
- Focused on **spin-1 sub-GeV DM** where $m_{A'} = 3m_X$
  - We find that spin-1 DM is the **first model** to be probed by LDMX in certain scenarios.
- Complementarity between experimental limits

- Soon: unitarity and direct detection limits
- Off-shell dark photon ($m_{A'} < 2m_X$)
  - Visible decay limits
- Spin-1 DM w axial + vector boson mediator
- Freeze-in spin-1 DM

Thank You!

Backup Slides

Sub-GeV Dark Matter



- Sub-GeV DM is largely experimentally **unexplored**..
  - Out of reach of nuclear recoil direct detection exps

- DM produced through freeze-out near weak scale
- GeV-TeV scale thermal DM already widely tested

Hadronic Resonances

- If DM freezes-out after the QCD phase transition (~150 MeV), DM annihilates to hadronic final states rather than to quarks.
  - Must consider for $m_X \lesssim 3 GeV$

$$\sigma v_{XX\to A'\to \mathrm{hadrons}} \approx R(s)\sigma v_{XX\to A'\to \mu^- \mu^+}$$

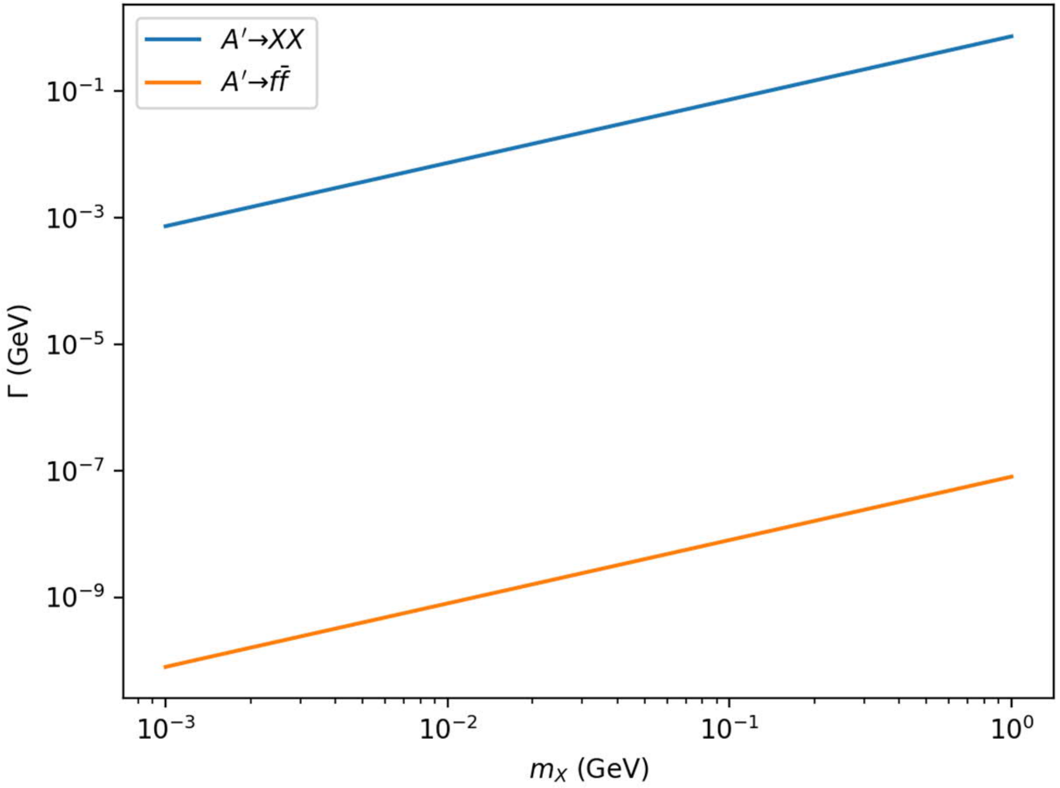
$$R(s) \equiv \sigma_{e^+e^-\to \mathrm{hadrons}}/\sigma_{e^+e^-\to \mu^+\mu^-}$$

Why $\mathrm{BR}_{\mathrm{A'\to XX}} > \mathrm{BR}_{\mathrm{A'\to \bar{f}f}}$ is a good assumption

For $\alpha_D = 0.5, \frac{m_{A'}}{m_x} = 3, h_3 = 0.001$:

$BR_{A'\to XX} \approx 0.9999999$

$BR_{A'\to ff} \approx 1.1 \times 10^{-7}$

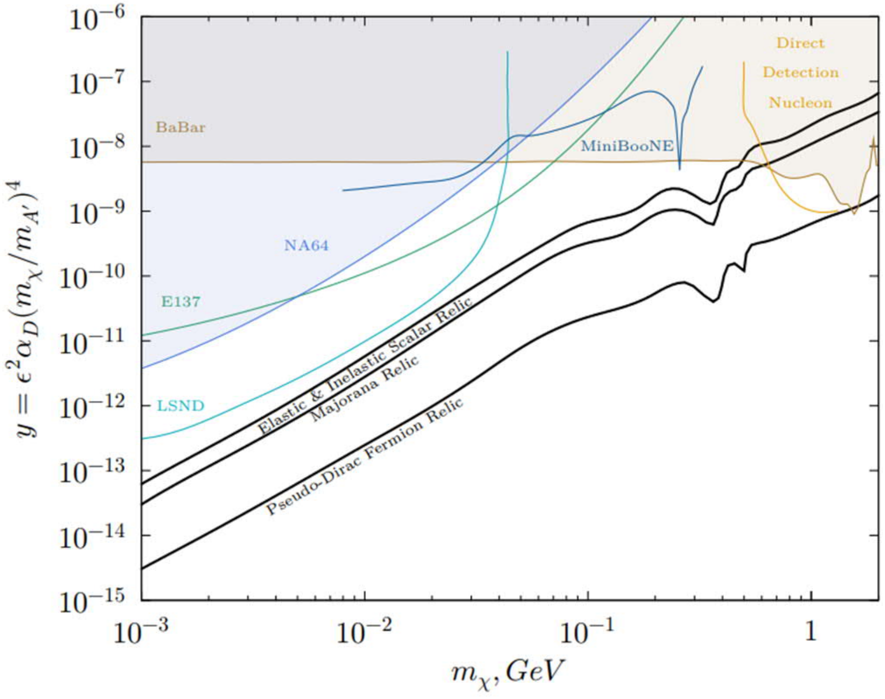


Thermally Averaged Cross Section Expansion

$$< \sigma v > \xrightarrow[\text{non-rel}]{} b_0 + \frac{3}{2} b_1 x^{-1} + \ldots$$

s-wave p-wave

Electron Beam Dumps



E137

arXiv:1406.2698

- Dark matter produced from electron-target collisions
- 20 GeV beam incident on a set of aluminum plates interlaced with cooling water.
- Downstream detector

NA64

arXiv:1710.00971

- 100 GeV electron beam incident on a lead target
- Event: single electron produced and missing energy

Proton Beam Dumps arXiv:1107.4580

- DM scatterings mimic neutrino scatterings! (Neutral current-like elastic scatterings)

Mini-Boone

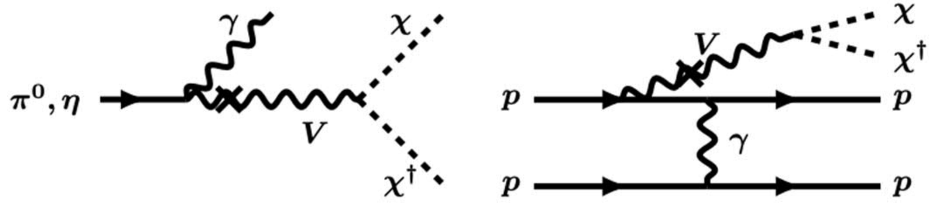
arXiv:1807.06137

- Designed to study short-baseline neutrino oscillations
- 8 GeV proton beam incident on a steel target
- Peak ~ 800 MeV (ρ mass)

LSND

arXiv:hep-ex/0101039

- pions produced by impacting an 800 MeV proton beam onto a water or metal target
- $\pi^0 \rightarrow A'\gamma, A' \rightarrow XX$



(a) π^0, η Decay (b) Proton Bremsstrahlung

FIG. 2. DM production channels relevant for this search with an 8 GeV proton beam incident on a steel target.

BaBar arXiv:1702.03327

- Search for single photon events in e^+e^- collision data
- BABAR detector at PEP-II B-factory
- Large missing energy/momentum
- Exclusions for $m_{A'} \leq 8$ GeV
- $e^+e^- \rightarrow \gamma A', A' \rightarrow XX$

Calculating Dark Matter Abundance: The Boltzmann Equation

$$\dot{n} + 3Hn = R$$

Universe's Expansion

Particle Physics

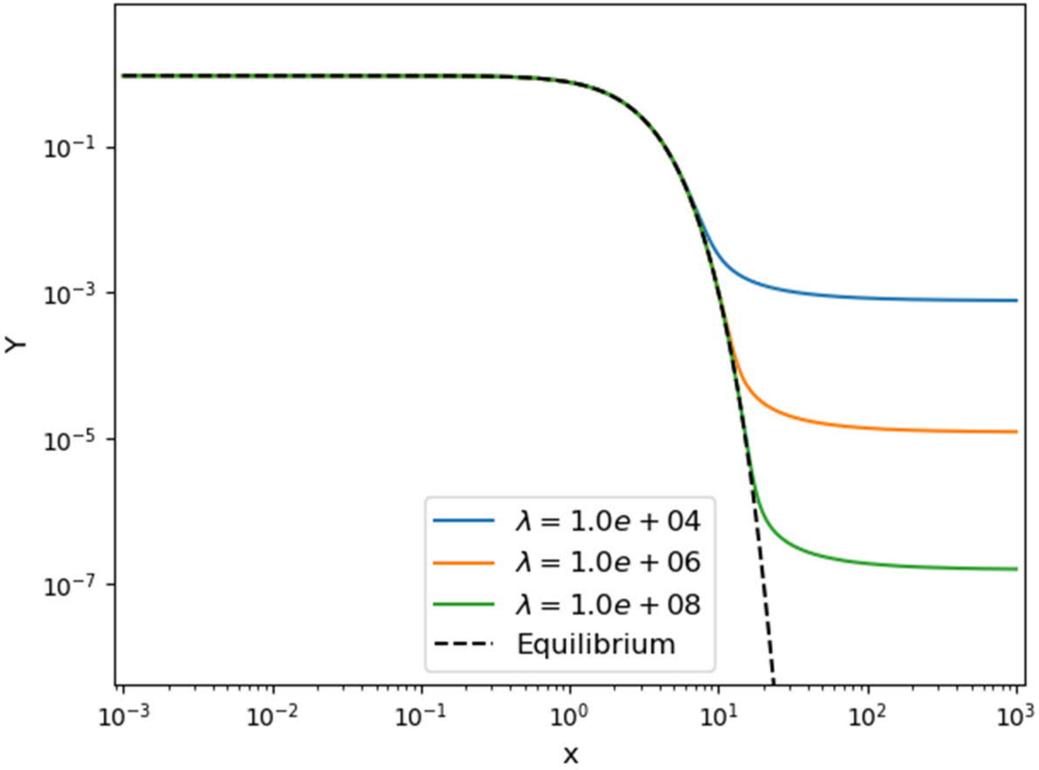
- n: number density
- H: Hubble Rate (Universe's Expansion)
- R: Interaction Rate Density (# interactions per time and volume)
  - Includes all annihilations and productions

- More convenient to define Y and x
  - $\mathrm{Y} \equiv \frac{\mathrm{n}}{\mathrm{s}}$, $\mathrm{x} \equiv \frac{\mathrm{m}}{\mathrm{T}}$
  - s: entropy density

Freeze-Out Calculation

For the process $12 \leftrightarrow \chi\chi$

- The Boltzmann equation:
  - $\frac{dY}{dx} = \frac{\lambda(x)}{x^2} < \sigma v >_{\chi\chi\to 12} \left[\left(Y_\chi^{eq}\right)^2 - Y^2\right]$
- Calculate freeze-out temperature $\mathrm{T_f}$
- After T_f, $Y_\chi \gg Y_\chi^{eq}$:
  - $\mathrm{Y_\infty^{-1}} = \mathrm{Y_f^{-1}} + \int_0^{\mathrm{T_f}} \lambda < \sigma v >_{\chi\chi\to 12} \mathrm{dT}$



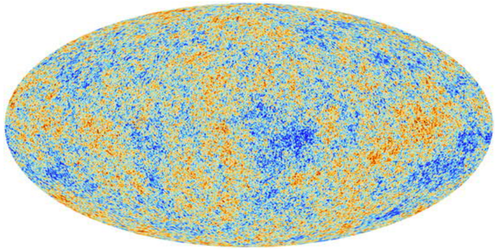
Dark Matter Evidence and Overview

Evidence:


NASA, ESA, J. Mack (STScI) and J. Madrid (Australian Telescope National Facility)

- Galaxy clusters
- Rotation curves of galaxies
- Large scale structure
- Cosmic Microwave Background (CMB)

Overview:



- Abundance $\Omega h^2 \approx 0.12$ (Planck)
- Interacts gravitationally with ordinary matter
- If it interacts non-gravitationally with ordinary matter it does very weakly